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Green Growth: From Intention to Implementation

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Since the end of World War II, the global economy has grown at a rate enabling GDP per capita to be doubled every twenty-five years. From 1973, growth has been redistributed, beginning with the rise of the emerging economies, in a correction of the protracted concentration of wealth in western countries and Japan. Fears that the scarcity of raw materials would impede this process have proven groundless. However, the impacts of population growth and economic expansion have the potential to disrupt important regulatory functions of global ecological systemes. Green growth involves transforming the production and consumption processes in order to maintain or restore these regulatory functions of the planet's natural capital.

Growth economists have clearly described how technical progress can surmount the barrier of natural resources scarcity. Models of green growth require that environmental factors be treated differently: they form natural capital that is an essential factor of production and not merely an externality. It seems that the growth process is eventually halted if sufficient investment is not directed toward this capital. But the implementation of this investment erodes the return from other factors of production in play, thereby raising new questions of distribution and equity.

In practice, the transition to green growth depends on advances being made in four areas: widening the concept of efficiency, thereby triggering new clusters of innovation; energy transitions, which anticipate and reflect the increasing scarcity of fossil fuels and whose rate and methods must be guided primarily by climate risk; inclusion of the value of natural capital in economic life; and a revision of the scale of risks within the financial system whose innovations for allocating resources at low cost to green growth would be greatly facilitated by effective pricing of environmental pollution.

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Introduction

Ever since the Sumerians, it has been known that growth driven by the accumulation of environmentally predatory capital eventually destroys itself: thanks to their knowledge of irrigation, the Sumerians originated writing, law and cities. But because it failed to master drainage, the vital complement of irrigation in arid areas, their civilization vanished as result of the soil becoming unproductive through the accumulation of salt. The people of Easter Island suffered a similar fate: after felling the last tree, they abandoned their island with its huge granite statues set in a lunar landscape. In a mineral environment, only stone can survive. Is our growth, like that of the Sumerians, in the process of faltering due to insufficient natural resources or the planet's limited capacity to absorb pollutants?

Green growth has been presented as a way of enabling growth to escape such limit situations, an alternative to the negative growth (or stagnation) to which the continued use of historical models would lead us. This type of representation has two main challenges.

The first is that it is extremely perilous to lay down the physical limits to growth. When Malthus' celebrated Essay on the Principle of Population (1798) appeared, Britain had 20 million inhabitants and the entire world a billion. Malthus believed that population growth then would quickly come up against the scarcity of farmland. The United Kingdom now has 61 million inhabitants and the planet seven billion; on the whole, humans are much better nourished now than in Malthus's time. Over the past 200 years, humanity has made technological progress unimaginable at the dawn of the 19th century. Have we become any more far-sighted, any more able to foresee the technological break-throughs of the 21st century?

The second challenge is that the conceptions of green growth describe an outcome without providing any indication as to the conditions required to attain it. As a result, it becomes possible to imagine as many green growth as non-green growth paths and even sometimes to disguise them, rename them and confuse them. The ministry of the environment will identify "green jobs". Experts will calculate that there is 25% "green investment" in one recovery plan, against only 10% in another. A manufacturer of sports cars emitting more than 250g of CO_2 per km will certify its assembly lines for their environmental performance, while another will sing the praises of its latest "zero emission" electric model, but fails to mention electricity-related CO_2 emissions. Absent a rigorous definition, "green" remains a nebulous concept, too easily misinterpreted and misused.

This paper offers a more rigorous concept of green growth in order that the conditions for its implementation may then be identified. Growth is understood here in its traditional economic sense: an increase in wealth measured in terms of production, income or living conditions. Growth is, *a priori*, neither "good" nor "bad". To describe it, it is necessary to examine the mechanisms linking the factors of production, the return on these factors, and the wealth produced. Growth is termed "green" when it properly treats natural capital as an essential factor of production, alongside labour and physical capital.

The paper is divided into three sections.

The historical perspective adopted in Section 1 relates the change of scale brought about by world economic growth in recent decades with the emergence of new issues such as the destruction of the ozone layer, global warming and loss of biodiversity. Within this perspective, the problem is not so much the lack of availability of a given resource, but the cumulative imbalance introduced into the vital regulatory capacities of natural capital. Restoring these capacities is the challenge for green growth in the coming decades.

Section 2 examines the conditions for implementing green growth through the formulation of a production function bringing together three factors: labour, productive capital and natural capital. This formalization allows us to explore the substitutability or complementarity between natural capital and productive capital. Two problems quickly emerge: how, given its heterogeneity, to put a value on natural capital; and how to calculate the return from natural capital, which refers to new questions of redistribution. To go from schematic representation to the real world, it is necessary to introduce a price of natural capital into the economic circuit.

Section 3 explores the ways this might be done in the real world, drawing on the lessons from the experience of carbon pricing undertaken within the framework in climate policies. Green growth appears first of all as a widening of the notion of efficiency. Such widening must apply to energy transition, which will be a key driver for this new growth in the coming decades. Its implementation involves settling new issues of distribution and equity, both nationally and internationally. It calls for financial innovations whose deployment would be greatly facilitated by effective pricing of environmental pollution.

1. The origins of growth: an historical overview

There have been many warnings in the past alerting us to the risk of an interruption in growth resulting from the depletion of natural resources: scarcity of arable land, of fossil energy, of water, fish stocks, rare metals, etc. Historians of growth reveal how society has managed to counter these successive threats through technological developments leading to the more efficient use of scarce resources, increasing their availability through investment in exploration or by finding substitutes. Has past growth therefore been a great deal "greener" than we thought? Answering this in the affirmative would be to overlook the fact that these many changes barely contribute to the restoration of natural capital, a highly sophisticated global system whose regulatory functions: climate stability, biodiversity maintenance, hydrologic cycling, etc., are threatened by our growth trajectories. Historical analysis provides a way of describing natural capital, not as an aggregation of finite resources, but rather as a set of regulatory systems that some forms of growth can disrupt and others strengthen.

A millennial perspective: the demographic foundations

Thanks to the meticulous work of Maddison (2001), we now have data on world economic growth over the last two millennia. Over this long time frame, it is evident to what extent the growth of humanity's productive capacity determines population.

From year zero through to 1000 AD, no driver existed to set in motion a cumulative wealth creation process. At the end of the first millennium, European productive capacity and living standards were lower than during the Roman Empire. Europe's population of around 25 million had stagnated, as had China's. Africa and Japan were probably sparsely populated, which would explain the very modest growth in the number of people in the world, rising from 230 to 268 million in a thousand years – a practically negligible change on a generational scale.

Between 1000 and 1500, competition began to arise between the two major centres of the global economy, namely the Chinese Empire and Europe. The two drivers of growth were agriculture and navigation. By the middle of the millennium, China probably accounted for a quarter of the world's wealth against a fifth for Europe. Despite the ravages of famine and epidemics, the Earth's population began slowly rising. Over five centuries, it more than doubled in Europe and a little less than doubled in China and other parts of the world.

Since 1500, agricultural productivity grew thanks to improved farming techniques and the gradual introduction of new crop species following the development of trade. Population growth rose to almost 0.3% per annum, with the global population more than doubling over three centuries to stand at over a billion people in 1820.

Population growth rates accelerated rapidly until the 1970s, driven by the dramatic decline in mortality rates among young children and women during childbirth. The rate then slowed as a result of a powerful downward trend in births that began in the richest countries in the 1960s and gradually spread to other geographic areas. The world has now entered a demographic transition period. The Earth's population could stabilize by the end of the 21st century at around 10 billion people – ten times that of 1820.

Table 1: World population

Year	Million	People/km^2
0	230	1.5
1000	270	1.8
1500	440	2.9
1820	1041	7.0
1913	1800	12.0
1950	2500	16.7
2010	6896	46.2
2050	*9306*	*72.3*

Source: A.Maddison (2001) and UN

While the global population has grown steadily, the land base, of course, has remained essentially fixed. Up until 1820, the planet was very sparsely populated, with an average of less than 10 inhabitants per sq. km. A fourfold increase in population over the 20th century produced a rapid increase in population density. By 2010, there were on average slightly less than fifty inhabitants per sq. km. If the Earth were transformed into an immense plot of land, each person would have slightly more than 2 hectares and would be just over 150 meters from his or her neighbour. In 1820, the figure would have had 14 hectares per person. In 2050, despite lower fertility extending to all demographic groups, plot sizes are likely be around 1.5 hectares. Green growth involves adapting modes of production and consumption to this unprecedented contraction in the space available for the natural habitat of a living species – the human species – which has become accustomed to domesticating or destroying many of its competitors.

A centennial perspective: interdependence and geographical polarization

The growth that began around 1820 in Europe was based on an unprecedented accumulation of capital for the transformation of raw materials into manufactured goods. Two key conditions triggered the shift: the taming of a new form of energy – coal – which massively augmented the working capacity of people and animals; and the acceleration of agricultural productivity, which allowed workers to be released from the land. The process was then continued through a succession of innovations that boosted productivity and resulted in the mass distribution of new goods and services thanks to lower costs. From the lighting revolution of the 19th and early 20th century analyzed by Fouquet and Pearson (2012) to today's microcomputer and mobile phone revolution, the process is the same.

After its beginnings in England, industrialization rapidly spread through Western Europe and to the four new countries where the population of European origin was quickly becoming the majority: the United States, Canada, Australia, and New Zealand. From the second half of the 19th century it spread to Japan following the Meiji Restoration of 1868. Up until 1950, other parts of the world were either partially carried along (Russia, most Latin American countries) or torn apart by the power of this process, which was accompanied by a fresh upsurge in European colonial conquest. From 1820 to 1950, growth in world output per capita was just under 1% per annum, representing a major break with the past. The United States and Western Europe grew faster than average, with the United States taking a decisive advantage in the 20th century, having escaped the massive destruction of the two world wars. Japan advanced at a rate close to average, while other countries regressed compared to the average: Africa, India and especially China, where the economy seemed to disintegrate throughout the period. According to Maddison's estimates, output per capita in China was lower in 1950 than it had been in 1820.

Table 2: GDP growth per capita since 1820

	1820	1913	1950	1973	2010
World ($ per capita)	670	1 510	2 110	4 100	10 886
World (%/yr over the period)		0.9%	0.9%	2.9%	2.7%
Position of different countries (100 = world average)					
Western Europe	185	230	217	281	279
USA	188	351	452	407	434
Japan	100	92	91	279	311
China	90	37	21	20	69
India	80	45	29	21	31

Source: calculated by the authors from Maddison (2001) and IMF data

1950 marked the turning point at which the disparity in growth between developed and developing countries shrank, and then reversed as growth in the latter outpaced the former. From 1950 to 1973, world GDP growth per capita was around 3% per annum. Japan and, to a lesser extent Europe, achieved record growth in reconstructing the capital destroyed by World War II. But the key fact is that no part of the world was any longer stagnating or in recession. India, which was the least rapidly progressing area from 1950 to 1973, had a per capita GDP growth of around 1.5% per annum and Africa 2% – relatively poor economic performance with regard to this period termed “the Golden Age” by Maddison, but very high compared to long-term trends.

The early 1970s was marked by two turning points: the collapse of the monetary system inherited from the Bretton Woods accord and the first oil shock. In 1973 the world experienced its first recession since the Second World War. Some commentators saw this as a signal heralding a lasting shift in the pattern of growth. The celebrated Club of Rome report on the limits to growth provoked unexpected resonance. These limits were presented in a way very similar to Malthus in his Essay: from now on growth will be limited by the scarcity of non-renewable resources, primarily oil. Some schools of thought even began extolling the benefits of degrowth.

Yet the world economy did not grind to a halt: the growth rate of output per capita was much the same before and after 1973, despite the sharp slowdown in Europe and Japanese stagnation since 1990. Its geographical distribution changed rapidly, though. Growth shifted to regions of the world with the lowest initial income levels, initiating a correction to the polarization of wealth in Western countries and Japan, which had been the system’s dominant feature from 1820 to 1950.

A decadal perspective: a shift in the world economy's centre of gravity

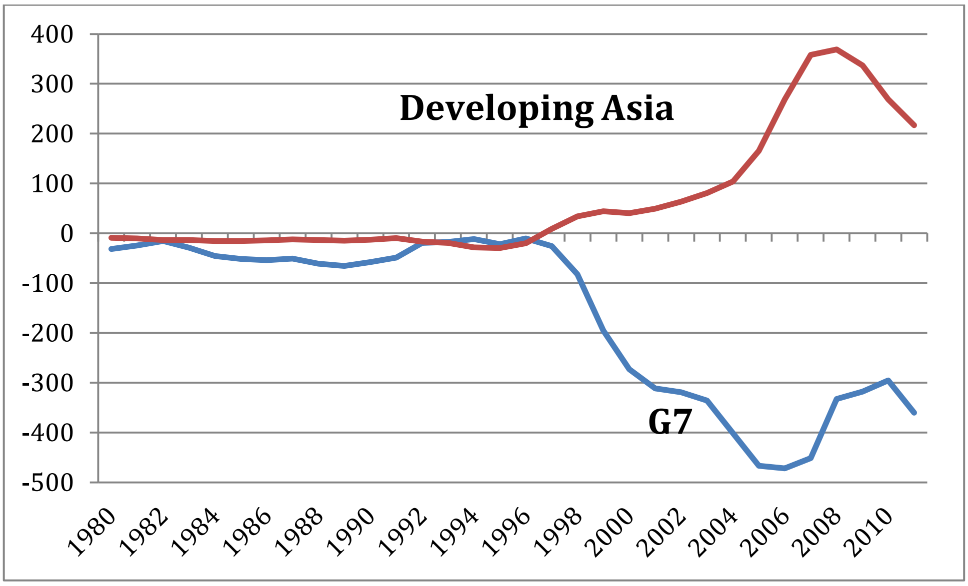
China, India, Brazil and some other countries have been accumulating capital at an unprecedented rate, enabling them since 1973 to begin a historic catch-up process. New forces have come into operation, which explain the speed of this redistribution. The opening up of trade took on a whole new dimension. In 1950, the volume of goods traded in the world economy was below its 1913 level. Between 1950 and 2000 it increased fourfold. Following market liberalization, finance capital became totally mobile. Information technologies facilitated the acquisition of new know-how, the spread of innovations and the interconnectedness of markets. Beginning with the take-off of small Asian nations, the process extended first to mainland China, which began opening up its markets in 1979 with the return to power of Deng Xiaoping, and then to the Asian continent's other giant country, India.

The spread of this dynamic to other parts of the world was not without setbacks. It took 10 years for Latin America to adjust to the new oil order, following the Mexican debt crisis that shook the whole continent during the 1980s. Africa struggled even more, with a decline in average income per capita between 1973 and 1998. The transition of the USSR from a planned economy into a market economy took place under the worst circumstances. The disintegration of the state and the application of the naively implemented liberal recipes of the Chicago school caused the economy to implode during 1990s.

The first decade of the new millennium amplified the redistribution of global growth, with its centre of gravity shifting to China and emerging countries. Latin America emerged from its difficulties of the early 1990s. Russia and its former satellites managed to halt their downward spiral around 1997-1998. Since 2001, Sub-Saharan Africa, the last major region of the globe hitherto left outside the redistribution process, has seen its per capita growth rise very strongly. In particular, the continent was able to resist the shock of the recession that undermined growth of the global economy in 2009.

As in 1973, the 2008-09 recession reflected a double shock: commodity prices and financial deregulation. Symbolically enough, the price of oil peaked in July 2008, two months before the bankruptcy of the investment bank Lehman Brothers, an event that revealed to the world the extent of the contamination of the financial system by excessive debt. But unlike the Mexican crisis of the 1980s or the Asian crises of the 1990s, it was no longer the periphery that was affected, but the very heart of the system, i.e. Wall Street, with its mountains of subprime debt, issued in the expectation of an indefinite rise in property prices. The recession was most pronounced in the old industrialized countries, and their recovery has been much less certain. To avoid a breakdown of the system, sovereign states, with the help of their central banks, assumed massive volumes of private debt. As a result, there is a reduced capacity for additional government intervention. Growth in these countries has been very slow to recover. By contrast, it rebounded quickly in emerging countries and in the developing world.

Figure 1: Balance of payments (billion dollars)



Source: IMF

Internationally, the impact of the 2009 recession reflects the new balance of power that has been developing since 1973. The internal debt crisis has been coupled with an unprecedented widening of current account deficits. Since 2000, the G7 has needed massive capital inflows, largely loans from developing Asia, to finance its growth. The shock of 2009 reduced the imbalance but did not eliminate it. Similarly, the financial crisis temporarily halted the surge in commodity prices, though this did not last: in 2011 as a whole, oil prices reached a new historic high. The emerging economies responded swiftly to these changes. They invested not only in U.S. Treasury bonds or the acquisition of Western companies, but developed strategies to secure their future supplies of energy, food and minerals. Evidently, there is a concern that natural resource scarcity, like debt, can negatively impact on growth. Are the conditions that spawned the 1973 recession again on the horizon?

Let us examine more closely the impacts of this historically unprecedented growth of natural capital. Three types of limits can halt the process: the depletion of non-renewable resources; the degradation of renewable resources through pollution; and deterioration of the vital regulatory functions of the natural system.

Growth and natural resources: the regulatory function of natural capital

Let's start with oil. Among the limits to growth identified by Meadows (1972), the depletion of fossil fuels has pride of place. The oil shock occurring in the year following the publication of his report seemed to confirm his prognosis. Another signal: oil production in the United States peaked and then began to decline in the 1970s, in accordance to what was predicted in 1956 by the geophysicist Hubbert with his well-known “peak oil” bell curve. Forty years later, it is clear that the physical scarcity of oil has not prevented global growth. The basic figures speak for themselves: in 1973, the International Energy Agency estimated that proven reserves of oil represented 40 years of consumption; in 2012, the figure is still 40 years of consumption, and considerably more if unconventional oil present in oil shale is included.

Three major adjustments have been made in the meantime to push back the wall of scarcity:

- Efficiency gains: in 2000 half the amount of oil compared to 1973 was required to produce the same amount of wealth in the world.
- Substitution effects: between 1973 and 2010, the share of oil in primary energy was reduced from a little less than half to a third.
- Increased investment in exploration and technical advances (horizontal drilling and hydraulic fracturing) that allow unconventional hydrocarbons present in all kinds of sub-soils to be extracted.

The rise of emerging countries hugely increases the economic resources devoted to this search for raw materials. And its continuation will no doubt further push back the limits of fossil fuel scarcity, to the point where another barrier, much more difficult to shift, will negatively impact continued growth, namely climate change, an issue that was absent from the debate on the limits to growth in 1973.

The geographical redistribution of growth between 1973 and 2012 led to an acceleration in emissions of CO_2, whose accumulation in the atmosphere toward the end of this period is reaching thresholds considered to be high risk by the scientific community. Contrary to commonly held ideas, higher oil prices resulting from its scarcity has not acted as a brake on greenhouse gas emissions related to energy use. The short-term efficiency gains have been eroded in the medium term by switches to other fossil fuels (especially coal and gas since 2000) and by incentives to extract a larger proportion of the oil reserves found in the sub-soil. Yet, as the scientific community makes clear through increasingly insistent messages, the use for energy purposes of all the carbon present underground would, on the basis of current technologies, constitute a major risk to the stability of our climate. Exploiting fossil fuel resources beyond a certain threshold adversely affects the capacity of the atmosphere to maintain climate stability. From the prospect of a physical limit resulting from the destruction of the stock of non-renewable resources, we have moved to the prospect of the deterioration of a major regulatory capacity of the natural system. But what is at work for the climate system also applies to other regulatory functions of our natural capital.

Thanks to the work of the Stockholm Resilience Centre, we can identify new critical planetary boundaries on which current patterns of growth risk rebounding (Table 3). These boundaries have been defined in relation to the risk of irreversibility, caused by the growth of human activities, on the major regulatory functions of natural capital. In the case of the climate system or the ozone layer, the limit can be defined only at a global level. This global aspect is a recurrent problem in international climate negotiations: no actor derives any specific benefit from more rapid or more costly action to address climate change. In the case of other boundaries such as the atmospheric concentration of aerosols, biodiversity or the fresh water cycle, these thresholds can be defined on different geographical scales, with their aggregation indicating a risk of irreversibility at a global level in response to continuing economic growth.

Table 3: Planetary boundaries involved in global growth

Earth system process	Control variable	Boundary	Latest data	Pre-industrial	Data source
Global level					
Climate change	Atmospheric CO2 concentration, ppm	< 350	387	280	IPCC (2007) ; NOAA (2009)
Ocean acidification	Global oceanic aragonite saturation ratio ($CaCO_3$)	> 2,75	2,9	3,44	Guinotte and Fabry (2008)
Stratospheric ozone depletion	Stratospheric O3 concentration, DU (Dobson : 1DU = 10µm ozone)	> 276	283	290	Chipperfield et al. (2006)
Local and/or global level					
Atmospheric aerosol loading *Not yet quantified*	-	-	-	-	-
Biogeochemical cycle (phosphorus and nitrogen)	Quantity of P flowing into the oceans, Mt yr^{-1}	< 11	10,3	1	Mackenzie et al. (2002)
	Amount of N2 removed from the atmosphere for human use, Mt yr^{-1}	< 35	121	0	Galloway et al. (2003, 2008)
Global freshwater use	Consumptive use of withdrawn runoff, ($Km^3 yr^{-1}$)	< 4 000	2 600	415	Gleick (2003) ; Shiklomanov and Rodda (2003)
Land system change	Percentage of global land cover converted to cropland, % (Mha)	< 15	11,68	5	Klein Goldewijk (2001); FAO (2008); Ramankutty et al. (2008)
Biodiversity loss	Extinction rate in number of species per million per year, E/MSY	< 10	> 100	1	Pimm et al. (2006); Mace et al. (2005)
Chemical pollution *Not yet quantified*	-	-	-	-	-

Source: Rockström (2009a)

Explanatory remarks. *The first three boundaries can be defined only on a planetary scale, and the other six combine thresholds that can be defined at different geographical scales. For example, the concentration of CO_2 in causing climate change is meaningful only on a planetary scale, whereas the concentration of aerosols also has major regional impacts in terms of health (respiratory diseases), the environment (acid rain destroying forests) and the climate (cloud formation and monsoon patterns). These boundaries are defined in relation to the risk of irreversible changes in the regulatory functions of natural capital. The variables used and the figures provided should be viewed as proposals and working hypotheses to be refined. The various boundaries are not independent of each other. For example, ocean acidification is linked in various ways to the carbon cycle and climate change.*

This relationship between different geographic levels may be illustrated through the example of agricultural resources. In the traditional Malthusian approach, the scarcity of cultivable land plays a potentially limiting role on growth in the same way as the geological boundary for oil. Among the justifications for European expansionism, the development of new agricultural land was long prominent, even though the colonial trade played only a very limited role in this area, mostly that of supplying urban centres with comfort goods: sugar was the main product imported from European colonies, followed by coffee, tea and cocoa. Europe’s food security rested primarily on the intensified agricultural improvement enabling the product per unit area to be increased locally. It was not until the 1960s and the “green revolution" that the intensification of food-producing systems based on adapted genetic selection, the use of chemical inputs and the expansion of irrigation enabled the newly independent developing countries to change the situation by very significantly reducing malnutrition in the world between 1960 and 1990.

These advances, absolutely unimaginable at the time of Malthus, nevertheless seem to be coming up against boundaries of various kinds. In economic terms, progress in reducing malnutrition has levelled off since 1990 and suffered a sharp setback with the surge in agricultural prices in 2008, which is putting many low-income consumers on short rations. As with oil, this tension reveals the existence of increasing pressure on agricultural resources. New forms of demand are also emerging: a growing demand for animal protein, which is much more costly in terms of natural resources, with the change in eating habits following the increase in living standards in emerging Asia; and the subsidiary demand for bioenergy since 2000 resulting from government support programmes for first generation biofuels in the U.S. and Europe.

The tension in agricultural markets also gives rise to problems on the supply side. Beyond certain thresholds, intensive farming models can disrupt natural systems of regulation, such as the fresh water cycle (groundwater depletion, pollution of surface water and groundwater, eutrophication, etc.). The extension of agricultural practices is one of the main factors causing loss of biodiversity, from which in return it suffers negative effects (classic examples being natural pollination for crops or living organisms in soils for their fertility). This extension can also contribute to climate change both through the expansion of cropland or pasture at the expense of tropical forests and through the growth of agricultural practices that produce greenhouse gas emissions.

Given all these complex interactions, the right criterion for combining agricultural development and the reproduction of natural capital is not so much the intensification of agriculture as the forms it takes: the general use of extensive farming would require too much land area, at the risk of affecting the major regulatory functions of natural capital (biodiversity, water, climate, etc.); while the systematic use of the dominant modes of intensive agriculture based on genetics and chemistry alters these control functions in a different way. The most promising approach is to invest in complementarities between the various components of natural capital in order to optimize over time the product per hectare. This “ecologically intensive” agricultural production (Griffon, 2006) serves also to strengthen the restorative capacity of various aspects of natural capital

Both for energy and agricultural produce, the limits to growth in terms of physical scarcity of natural resources have been pushed back in the course of the last four decades. Rising prices in world markets, then the shock of the 2009 recession, have reminded us of pressures that continue to be exerted on these resources. These constraints have given rise to investment strategies aimed at securing supplies, in relation to which the emerging countries now occupy a new pivotal position alongside the developed world. This situation increases the finance committed and is likely to extend the use of these resources to the detriment of the essential regulatory functions of natural capital such as climate, biodiversity, the water cycle, etc.

The challenge for green growth is to shift from the race to secure supplies of non-renewable resources that is already taking place on a world scale to another race, one that seeks to maintain the regulatory functions of the natural system, thereby ensuring the reproduction of renewable resources, including those which humanity has long believed to be unlimited, such as fresh water, air, the sea, etc. This green growth challenge refers to the type of capital accumulation practised to increase wealth: can the emerging countries avoid going through the various stages followed by western countries and Japan, the reproduction of which would greatly increase the pressure on natural capital? How can the old industrialized countries re-orient their modes of production and consumption, given the weight of existing infrastructure? In both cases, do the required transitions constitute growth drivers or should they lead us to accept lower growth in the name of preserving natural capital?

To grasp these issues clearly, let us now examine how economists incorporate the natural capital dimension in the analysis of growth.

2. Towards a production function taking account of the environment

Economic theory conventionally analyzes growth as a combination of human capital and productive capital, with the deterioration of natural capital and its regulatory functions as associated or inevitable outcomes. Economists' responses to the setback of the early 1970s and the celebrated "end of growth" advocated by the Club of Rome, largely concentrated on showing the role of technological progress in overcoming or pushing back the limits of the scarcity of natural resources. In this section, we adopt an approach that takes into account not only pollution but also natural capital as a production factor. This approach requires that natural capital be conceived as a source of growth, if we are to renew it and make it be productive. The reader will find details of the formalization and the problems it must solve in the Technical Annex.

Sources of growth in the standard view of production

From the viewpoint of standard theories of growth, economists are generally in broad agreement on the role of two key elements: human capital and productive capital.

Human capital (H) represents labour in terms of its contribution to production. This concept encompasses both purely demographic aspects (birth rate, longer life, immigration), and aspects of labour productivity in terms of skills (education). In theories of growth incorporating human capital, the important thing is the augmentation in the labour force quantitatively or qualitatively. In the latter case, it is the accumulation, in principle limitless, of knowledge that is central to growth. By enhancing the educational level, we augment *ad infinitum* the production capacities of the economy. One of the myths willingly ascribed to the digital economy is that this occurs without reference to the necessary production of real goods that accompanies this growth.

The second element concerns the increase of productive capital or physical capital *(K)*. Productive capital includes all investments, machinery, tools, infrastructure and inputs other than the labour involved in the production of wealth. An increase in productive capital entails an investment effort that boosts the amount or performance of fixed capital in the economy. For growth, as well as the labour force, the important thing is therefore the quantitative or qualitative augmentation of physical capital.

In a simplified depiction of the production process, the combination of these two factors of production (capital and labour) is shown by a production function representing all possible combinations between the factors and accounting for the level of production *(Y)* of an economy: $Y = F(K,H)$. On this basis, innovation, knowledge and technical progress allow the productivity of the factors to be raised either individually or for the whole production function; in this case a multiplicative factor completes the representation, $Y = A\ F(K,H)$. We can then consider, as in classic growth models, the existence of global externalities taken into account in the multiplicative factor *A*. This factor incorporates either technical progress, or the average level of human capital, $A(H_M)$, or the average level of physical capital $A(K_M)$. We thus obtain a production function with increasing returns and therefore potential growth in the economy. In these systems, all that matters is the capacity to increase the factors of production, in other words the accumulation of physical capital, the accumulation of human capital and the multiplicative factor, without considering the potential environmental effects.

A large number of growth models can then be envisaged, whether it be a matter of exogenous growth linked to fortuitous technical progress as in Solow's (1958) model or endogenous growth linked to linked to human capital (Lucas, 1988; Rebelo, 1991), physical capital (Romer, 1990) or public investment in education or research and development (Barro, 1996). All these approaches are ultimately concerned with the elements constitutive of the production function.

In response to the Club of Rome, authors such as Dasgupta and Heal (1974, 1979), Solow (1974) and Stiglitz (1974) proposed taking into account the effect of technical progress or the substitution between physical capital and exhaustible resources *(R)*: $Y = F(K,R,H)$. By introducing an exhaustible resource into the production function, they show that the limits of growth are less a matter of the depletion of resources than the capacity either of technical progress or substitution between the factors of production to ensure growth.

This approach based on technical progress and numerous historical observations enables us to overcome the pessimism of classical authors around potential long-term growth. The simple view of Ricardian rent emphasizes the effect of diminishing returns in agricultural production as less productive land is brought under cultivation. Indeed, this rent is the difference between the cost of production from fertile land and the cost of production from less fertile land. By gradually substituting physical capital (chemical inputs, mechanization, irrigation) and human capital (agronomy, genetics) for land, agriculture seems able to escape the physical limit of yields from the land.

In approaches involving technical progress, it is possible to obtain infinite growth even in an economy whose development is based on a finite resource. Indeed, if we accept that technological progress can continually compensate for the depletion of the resource, then infinite growth is possible. Intuitively, if we use 10 litres of gasoline to drive 100 km, and our gasoline reserve is 100 litres, then without technical progress we can expect to travel a maximum of 1000 km. By introducing technical progress that allows us to drive 500 km on 10 litres of gasoline, then we can go 5000 km. So if we constantly improve our consumption performance then it is not impossible to travel an unlimited distance with the last drop of gasoline: the progress of human intelligence will have find perfect substitutes to ensure our mobility without gasoline. Thus without too much difficulty we can imagine infinite growth in a finite world.

The historical analysis carried out in Part I recalled that beyond limits to growth based on resource depletion, we must turn to externalities. Although technical progress and substitution between factors of production suggest that we can circumvent the depletion of natural resources, there are nonetheless still limits how much the planet can withstand. There is probably more to fear by way of damage to the conditions for reproducing resources, disruption of regulatory systems and loss of biodiversity than the potential depletion of resources. How can we incorporate pollution into our reasoning?

The introduction of pollution into the production function

Consider the production of a good that generates pollution. With the production technique unchanged, a decrease in pollution implies a decrease in production. It is as if pollution were a factor of production. Approaches such as those of Copland and Taylor (1994), Stokey (1998) and Jouvet *et al.* (2005) illustrate this very simply. Consider our standard production function. By introducing a use index of the technology, Z, between 0 and 1; Y = ZAF (K, H) and assume that this production contributes to pollution designated E. We can then define a pollution intensity with respect to production. We note that I(z) = E/AF (K, H). It is then relatively easy to substitute our technology index between output Y on the one hand and the intensity of pollution on the other. We obtain a production function directly incorporating pollution as a factor of production: Y = AV (K, H, E). In this first step, we no longer view pollution as a simple consequence of the production process but as a factor contributing to production. This shift results from the fact that there is a complementarity between pollution and other factors of production used.

Consequently a proportion of the production linked to traditional factors of production is attributable to pollution. In our stylized case, we thus see a reduction in the respective weight of physical capital and human capital in production offset by taking the environment into account. This reduction amounts to a loss of revenue equal to the cost of pollution. If pollution is considered as a factor of production, then the productivity of the two other factors are overvalued at a given level of production. The productivity of these factors, and hence their returns, must be corrected (Brechet and Jouvet, 2009).

This approach is in principle somewhat different than our vision of “green growth”, which is to “promote growth and development while reducing pollution and greenhouse gas emissions, minimizing waste production and waste of natural resources, preserving biodiversity and enhancing energy security” (OECD, 2011). It nevertheless has the merit of underscoring that some of the productivity attributed to conventional factors of production comes ultimately from environmental degradation. But it continues to define the green growth by default.

Let us now attempt to consider the environment as a factor of production. It is therefore no longer a matter of thinking of natural capital in terms of limitation or protection, through taxes or regulations, but in terms of expansion.

Natural capital as a factor of production: the shepherd and sheep shearing

Take the simple case of a shepherd living from his capacity to produce wool by shearing sheep and washing the raw wool. Let us assume that our shepherd is something of an expert at his job, with 10 shearings and 5 clean fleeces an hour. The owner decides to conduct an experiment and asks the shepherd to shear the sheep and wash the fleeces without using water. As this is considerably more difficult, the shepherd can still shear 10 sheep but manages to wash only two fleeces an hour. In this instance, the productivity of the water resource corresponds to the missing three fleeces. Part of the creation of value is attributable to water.

If this water becomes unusable as a result of pollution, the shepherd's productivity falls. The paradox is therefore that pollution is a factor of production, as Stokey's model shows, but it produces its own limits on the very conditions for the reproduction of the factors of production. It is this retroactive effect that we must try and depict.

Like productive capital or human capital, natural capital covers a large variety of components, from renewable or exhaustible natural resources through to the full range of ecosystem services. Resource-related components are not difficult to understand, whether they be exhaustible resources such as oil, coal, gas and uranium or renewable resources such as forest, agriculture and fisheries, biodiversity (defined in terms of genetic) and water. We are generally able to conceive of these without much effort. It should be noted that the use of resources often requires immobilization of physical capital, but in the case of renewable resources it also requires the existence of natural regulatory services that allow their reproduction. The deterioration of such services may in fact result in the depletion or disappearance of good previously considered "free", i.e., available in unlimited quantities: water, air, the stability of the climate, biodiversity, and so forth.

When we focus on the various services provided by nature, the spectrum tends to widen:

- production services – e.g. food, energy resources, water production, pharmaceutical resources, genetic resources or ornamental resources
- regulatory services - e.g. atmospheric quality, erosion, water purification, climate regulation, absorption of the effects of natural hazards
- primary services - e.g. soil formation, photosynthesis, the water cycle and the cycle of nutrients essential to life, and
- cultural services involved in creativity, inspiration, educational values and various recreational activities ranging from the contemplation of a landscape to outdoor sports.

In a retroactive way, deterioration of these services may negatively impact our production capacities directly or indirectly. For example, air pollution can degrade human capital, generating a significant cost for the whole economy. Similarly, the loss of biodiverisity, increased scarcity of forest resources and deterioration of groundwater each constitutes a degradation of productive capital.

Clearly, natural capital plays a significant role in the productivity of the two factors of production traditionally taken into account. It follows that some portion of the creation of value is attributable to natural capital.

Exogenous and endogenous growth models assign a key role to the global parameter, A, of the production function and attempt to shape it. If we accept that the reproduction conditions of human capital and physical capital partly depend on the state of the environment, then the multiplicative factor of the production function must depend on the overall quality of our environment (Q), i.e. A = A(Q). Thus, the production function incorporating the environment depends not only on pollution emitted during the production process but also on the accumulation of this pollution, P, which alters the conditions under which production occurs. Viewing the quality of the environment as a decreasing function of the total amount of pollution, P, it is evident that the pollution flow constantly being emitted will increase the total stock by degrading the conditions of production itself. The model developed in the annex shows that above a certain level, this retroaction leads to zero production, i.e. to the disappearance of the economy. The quality of the environment becomes a constitutive component of growth. We need therefore to devise a model that can successfully make a connection between pollution both as a factor of production and a cause of limitation of that growth.

These production factor aspects should make us think not only about the distribution of wealth among the factors of production, but also about the conditions for production growth. Investing in environmental quality implies not only a reduced role of pollution in production but also an improvement in overall production conditions and therefore in growth conditions.

Table 4: Production function formalization

Function form	Externalities inclusion	Authors
Y = AF(K,H)	Exogenous technical progress	Solow(1956)
Y=AF(K,H,R)	Resources depletion	Solow(1974) , Dasgupta et Heal (1974) , Stiglitz (1974)
Y = A(X) F(K,H), X= K, H	Endogenous technical progress based on human (H) or physical (K) capital	Romer (1990), Lucas (1988), Rebelo (1991), Barreau (1996)
Y = F(K,H,E)	Pollution in the production	Stokey (1998), Copland et Taylors (1994), Jouvet, Michel et Rotillon (2005)
Y = A(Q) F(K,H,E)	Pollution and environment quality in the production	Authors' approach

Source: Authors.

Then we need to consider the question of factor returns.

Natural capital and returns to factors of production: who pays for the water used for shearing?

Let us go back to the sheep owner, who pays the shepherd according to his ability to produce clean wool. The shepherd receives an hourly wage equivalent to the wool produced in one hour, or the equivalent of either two or five fleeces depending on whether the washing is done dry or with water.

As long as access to water is free, the distributive question does not arise: it is in the interest of both the owner and the shepherd to draw on this natural resource to increase their respective profit and wage. Suppose now that water resources become scarce, and water has to be paid for at a rate equivalent to half the shepherd's hourly wage. Who should pay the bill? Conversely, investing in the water supply needed can lead to increased overall production. Who then will be the beneficiary? These are key questions for the implementation of green growth.

One of the fundamental principles of economics is that each factor of production receives a proportionate share of the wealth created as part of its contribution to total wealth, i.e. a "fair share" of value creation. Each factor of production can be varied with any degree of fineness: in principle, none are forgotten. Human capital can range from the employee with no recognized qualifications to the senior manager with a string of degrees, productive capital from the hammer to the nuclear power plant. In this simplified world, employees receive a proportion of human capital and the various owners a proportion of productive capital (for their role in creating value). Everyone consumes and saves in accordance with their income and their preference for different goods. This theoretical economy works perfectly well, and increases in the different factors of production are the source of growth. All that remains now is to determine the actual share of each factor in creating wealth, in other words on all the parameters of the production function.

The introduction of natural capital into the production system changes the returns to traditional factors of production. Alongside the wages and profits that allow the reproduction of labour and capital, we add the environmental rent needed for the reproduction of natural capital. The rent must be deducted from existing revenues. If the natural capital is a source of pollution, such as the use of coal in an electricity generating plant, it is appropriate and reasonable that deduction of value is made on the return to the capital. If it is the combination of labour and capital factors that is the source of pollution, then the deduction should be made in proportion to the contribution of each factor to the production process. In both cases, the initial distribution of wealth between factors of production is changed because they are allocated a proportion of the productivity that is in fact attributable to natural capital.

The example of CO_2 emissions pricing in Europe

Here the example of European CO_2 emission allowances is instructive. By deciding to set up an emissions trading market in the context of its climate change policy, Europe directly places CO_2 emissions into the production function. Allowances play the role of a factor of production in the same way as capital and labour. They are not simply financial assets. In order to produce, a firm subject to the ETS needs capital, labour and natural capital in the form of energy resources and CO_2 allowances. Production was previously a function of two factors; now it is a function of three.

The total value of CO_2 allowances is comparable to a rent, arising at the moment when all emissions from European industry was capped: emitting two billion tonnes of CO_2 (the approximate quantity of allowable emissions during the period 2005-2012) was free prior to the introduction of the emissions trading scheme. If there is an average price of 15 euros per tonne, these emissions have now a market value of 30 billion euros. This rent represents the value of Europe's emission reduction commitment. Let us now look at the choices made regarding the allocation of this carbon rent.

Taking into account this third factor of production does not a priori determine how this wealth is redistributed. During the first two periods of the ETS, most allowances were freely distributed to businesses. This option allowed Europe to avoid the difficult question of what proportion of income, wages or profit to take in order to finance the reproduction of natural capital. The lack of any trade-off came at the expense of European public finances, which relinquished the flow of potential revenue. But was this option wise for growth? The return of the carbon rent to industry is a subsidy. It could be beneficial if its recipients invested it massively in a low-carbon economy. This did not happen. Consequently, most European governments continued subsidizing the deployment of renewable energy. The decision was taken to sell the majority of CO_2 allowances by auction in the third period.

From the moment the public authority receives the value of the carbon rent – perfectly legitimate given the public good character of the atmosphere – the distributive impacts of carbon rent must be carefully examined. If payment for CO_2 allowances by firms occurs at an unchanged rate of profit, it is as if the owners of productive capital were the owners of the environment[1]. The sheep farmer is the owner of the water; the beneficiary of Ricardian rent is the owner of the Earth's fertility. This option would be green growth that might be described as capitalist, in which employees and consumers have to support the entire burden of adjustment. If the owners of productive capital are enterprising, this option can generate new capital accumulation that is very beneficial for green growth. More likely, absent sufficient counterweight on the side of labour and consumers, the dynamic would be blocked by rising social costs.

If we consider that natural capital affects the entire productive system, then part of profits should also be trimmed by a carbon rent. In this case, it is logical to reduce wages and profits in proportion to their previous contribution to production. If the holders of labour and capital are to maintain the same level of earnings, they will have no way in the short term other than passing the bill on to consumers, a possibility that will depend mainly on the form of the corresponding goods and services markets.

This option is socially acceptable, but is it favourable to green growth? The answer depends on the incentive to invest and companies' responses to it. If the carbon price is sufficiently high, holders of capital will have the possibility of regaining the average profit rate of the economy by investing in the means of production and distribution of low-carbon energy. The effect is very favourable to more balanced green growth. Conversely, the risk is that the falling rate of profit diverts capital from these sectors, causing a decrease in investment or its flight to geographical areas where there is no carbon price. To avoid social costs in the short term, we risk sacrificing growth and the long term.

From the example of CO_2 to its generalization: a typology of green growth

Now suppose one is able to price all the components of natural capital, the reproduction of which is now ensured through an environmental rent. The shift from a two-factor production function to a three-factor function linked to three revenue streams – wages, profit and rent – allows us to sketch

[1] Within the limit of the emissions cap.

the outlines of several green growth scenarios. We can broadly distinguish three models, all of them contrasting with "cosmetic" green growth, the main features of which we begin by recalling.

If natural capital is kept virtually free, which for the moment seems to be the norm, we have a form of "convenience" green capitalism, whether private or state-based. The introduction of an environmental tax of a few cents on white goods is not going to change consumption or production behaviour, but may send a message about an environmental problem.. It is "green growth lite". We introduce small taxes here and there in the name of the environment, while taking care that none of them is likely to overly disturb production and consumption behaviour. At the same time, we appeal to people's public-spiritedness, provide them with better information on environmental issues, and to the voluntarism of the business community and investors, who are expected to be "socially responsible". This type of compromise is easy to find: nobody wants to pay higher prices for the goods and services they consume. Similarly, few investors want to see their expected returns on accumulated productive capital eaten into by environmental charges. By not changing the relative proportions of all production factors, by not bringing the environment into the production system, these compromises will fail to produce a new growth dynamic.

If we augment natural capital to the detriment of labour, we are then in a situation of "market-based" or "state-based" green capitalism. The return to natural capital is taken directly from the productivity of labour. It is then up to employees to try and increase their productivity if they want to avoid a deterioration in their income or an even greater tendency for wealth be distributed in favour of capital. Another feature of this type of green capitalism is the belief that productive capital alone proves to be virtuous in terms of environment (solar energy, wind power, electric cars, etc.), while labour, in its current form, finds itself in a no-win situation and must agree to reform and adapt to the new environmental deal. The cost of adapting is by no means neutral and the introduction of new productive capital is likely weigh heavily upon labour, as will be recalled from the collapse of the textile or steel industries. Although new jobs are created, how many will have to disappear? And will the balance be positive? The question arises insofar as green capitalism does not change social relations, but lengthens the life expectancy of existing ones through the imposition of an environmental rent paid ultimately by labour. The environmental costs of growth are therefore likely to be passed on as social costs.

In contrast, if we imagine an augmentation of natural capital at the expense of productive capital, we then have a post-capitalist growth model in which productive capital adjusts to natural capital. In this case productivity changes only apply to physical capital. Growth then comes about through the development of human capital and the preservation, repair and development of natural capital. This implies considerably readjusting the return on productive capital in order to fund natural capital; in other words, it leads us to view natural capital as a paying investment, and requires obtaining a return on natural capital even in the short term. This prospect seems fairly unrealistic. Indeed, enhancing natural capital often requires beginning with major large investments in physical or human capital. The production of renewable energy or efficiency gains in buildings or networks call for large capital investments at the outset that will never be made if the initial return on physical capital is too low. In addition, the considerable productivity gains that can be generated by ecologically intensive agriculture require large investments in knowledge. It is for this reason that this second path risks quickly leading to a deterioration in growth or even negative growth, through too great a reduction in the returns from productive capital.

Between these two routes outlined above, a third green growth route emerges in which the return on natural capital is achieved by the reallocation of revenues from labour and capital in proportion to their initial contributions to pollution. Taking into account the environment in the production function should lead to greater attention to opportunity costs; in other words, to the fact that putting a price on environmental destruction enables additional costs to be avoided through more careful management of natural capital. These beneficial effects may facilitate the shift to a new distribution of income between labour and capital and an alternative (higher or lower) provision of social services. This raises concern for the most vulnerable members of society, in particular. But one thing is certain: we will not turn growth green without a serious savings effort, weighing on returns to both labour and capital in order to ensure a sufficiently large rent to rectify the performance of natural capital, in particular by restoring its major regulatory functions. It is important not to give the illusory impression that with green growth we get “a free lunch”: exactly the opposite is the case, since the need to save is greater, at least at the outset. Let us now see how we can approach this new kind of growth from the instruments that are available in the real world.

3. The implementation of green growth

Implementing green growth involves refocusing the investment effort by including natural capital among the factors of production. Such investment has an initial cost, on which the returns depend on the type of innovations generated and the spread of new goods and services resulting from them. We are now interested in mechanisms that can bring about the transition to this new kind of growth. As a first approach, we have identified four levers that, in combination, could serve as a catalyst.

Broadening the notion of efficiency

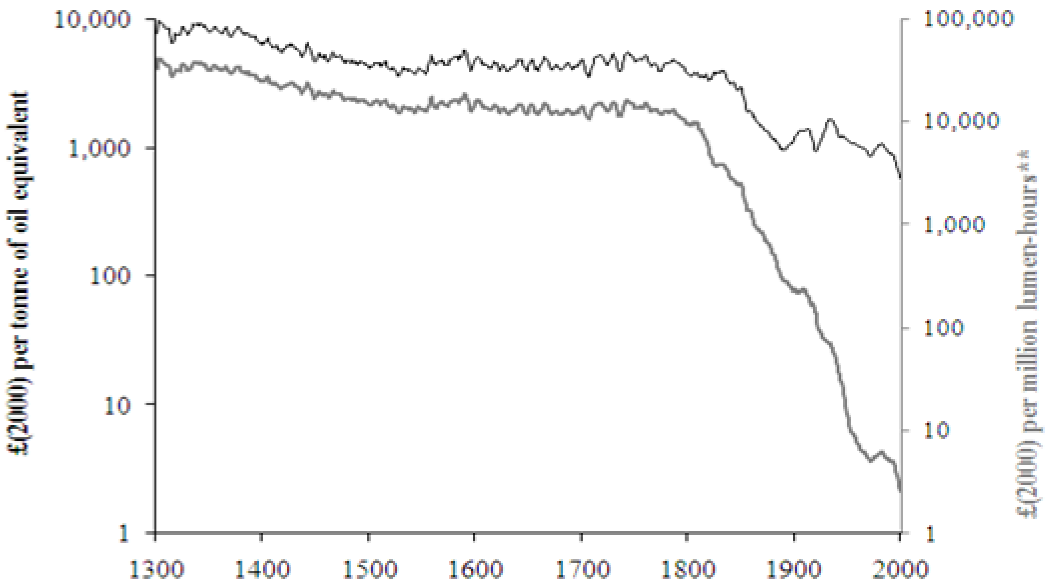
One of the supposed advantages of the market is its generation of efficiency in the use of resources. And in fact there are a host of remarkable productivity gains that have allowed the spread of new goods and services thanks to lower prices. Consider, for example, the cost of household lighting, which has fallen by a factor of 3000 over two centuries in the United Kingdom (Fouquet, 2011).

Yet for all that has our society become more efficient? Lean production, the watchword of industrial organization perfected by Toyota, allows work to be optimized throughout the production chain. But why struggle to get the most out of every minute of work inside the factory when thousands of unemployed can no longer find work outside? The industrialization of logistics chains leads to an unbelievable abundance of food products in our supermarkets, sourced from every geographical location and available whatever the season. Yet how efficient is all this abundance when more than 40% of products are wasted and some of those consumed give rise to new pathologies linked to overconsumption, such as obesity and cardiovascular diseases? Competition in car markets makes manufacturers constantly improve efficiency and safety: on average, a European mid-range car can travel twice as far than thirty years ago with the same amount of fuel. Yet where is the efficiency in terms of mobility when ever more cars burn this fuel as a pure loss, stuck in traffic jams resultant from too many vehicles on the road?

The transition to green growth consists first of all in broadening the very concept of efficiency. Work carried out at the Wuppertal Institute in Germany has for twenty years been exploring how this might be done. It came up with the simple idea that investing in the efficiency of all resources would allow society to consume as many goods and services, while reducing by a factor of five the use of non-renewable or polluting resources (Von Weizsacker, 2009). Broadening the notion of efficiency produces a threefold shift in the functioning of the economy.

The optimization of utility depends less on the quantity of goods and service consumed than on their capacity to provide the services required (Von Weizsacker, 2009). These two variables are far from being equivalent in the long term. Consider the case of lighting, whose large-scale spread amounted to a major revolution in how society is organized. As Nordhaus (1996) and Fouquet (2011) show, it was the technological breakthroughs upstream that allowed leaps forward in productivity, making possible its spread on a very large scale: the oil lamp, then town gas replacing candlelight, the incandescent bulb that took more than forty years to take over from gas, and finally low consumption bulbs. With green growth, we move from an economy of force-feeding consumers with goods and services to an economy of functionality in which there is investment in efficiency of use.

Graph 1: Price of lighting service and energy used (United Kingdom, constant £)



Source: Fouquet, (2011) (reproduced with the permission of *Energy Intelligence*).

From this economy of functionality there naturally follows the concept of the circular economy in which the raw materials used to produce certain goods and services are recycled to produce other goods and services. Some circular economy pilot projects, like that of Kalunborg in Denmark, are based on the use of simple complementarities between heavy industries that generalize the principle of co-generation. The stakes of the circular economy for green growth are considerably higher. They involve bringing into general use products whose design and cost must include from the outset 100% re-use of end-of-life-cycle raw materials. Another key element is the large-scale development of biogas, enabling the recycling into energy of all sub-products and waste from agricultural and food goods.

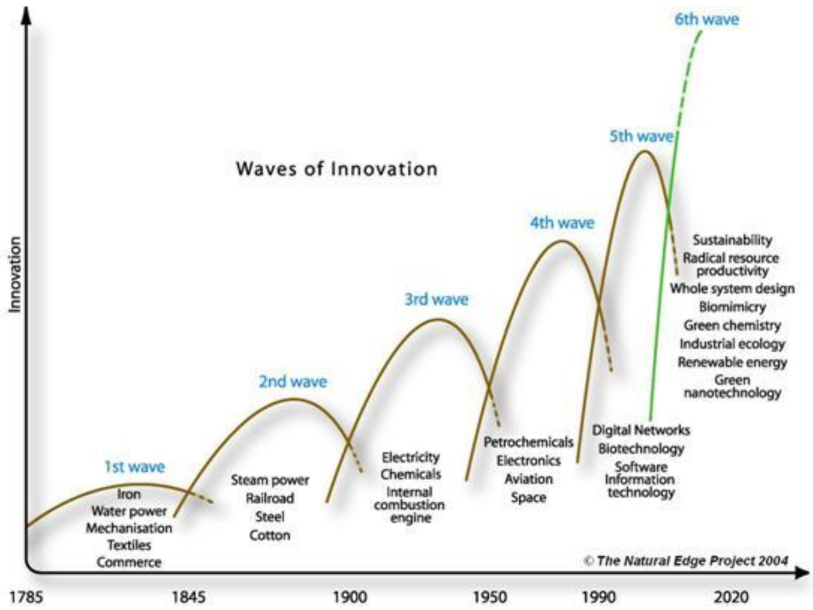
A third element of the efficient management of resources consists of making sensible use of what is termed "the rebound effect". This effect is generally viewed as negative, since it can consume part of the natural resource economies anticipated through advances in efficiency. If the elasticity of demand for the goods concerned is greater than one, there will be an increase in consumption of this resource, as Jevons showed in the 19th century in his celebrated essay on the driving role of coal in the industrialization of the United Kingdom. As Ryan and Campell (2012) remind us, gains in energy efficiency can have a variety of beneficial effects. For example, one of the current forms of energy poverty stems from the poor energy performance of dwellings occupied by disadvantaged social classes who are obliged to ration their consumption. Improving this performance is a good way of enabling these household to cover their basic energy needs. At a global level, these efficiency gains are one of the conditions needed to widen access to energy in a world where nearly one and a half billion inhabitants have no electricity and energy security is an increasing concern in developed countries. It is a green growth priority to make a large-scale contribution in this respect. How can we avoid the rebound effect being diverted from this type of use to superfluous consumption and waste of resources? By correctly pricing rare resources, beginning with fossil fuels, where the price should reflect both their exhaustible nature and the environmental risks associated with their use.

Energy transition, the driver of green growth

Each of the main periods of growth described in the first section has been underpinned by the domestication of particular forms of energy, making possible the large-scale spread of new goods and services: coal and the production of steam with railways and the steel industry; oil and the internal combustion engine; electricity, lighting and many industrial processes, etc. These waves follow on from each other every 30 to 50 years, recalling the long growth cycles described by Kondratiev.

From one wave to the next, the energy system transitions from a state relatively more dependent on biomass to a state relatively more dependent on fossil fuels. The proportion of fossil fuels peaked in the early 1970s: in 1973, oil, coal and gas represented 80% of the primary energy used worldwide. Forty years later, the proportion of oil has fallen from around half to a third. But the proportion of fossil fuels has remained at 80% because of increased use of gas and coal. Our addiction to fossil energy has stopped growing, but it has not declined. The next wave of innovation generated from the energy system will be the diversification of sources and modes of production and distribution of the energy needed to reduce to our dependence on fossil fuels. Because of climate change, this transition must take place quickly: in forty years we must be able to reverse the 80-20 proportion by developing carbon capture and storage technologies to enable us after 2050 to use the residual 20% fossil energy virtually without emitting CO_2 into the atmosphere. In economic terms, this is conceivable only if energy prices reflect both the geological scarcity of fossil fuels and their destabilizing impact on the climate system.

Figure 2: Growth cycles and key innovations



Source: Von Weizsäcker (2009)

The standard economic model for managing a non-renewable resource is pricing its scarcity through a rent that is added to the price of the resource as its finite stock is depleted. Although perhaps chaotically, traditional raw materials markets price the Ricardian scarcity rent associated with the non-renewable character of fossil fuels: everyone can see that the cost of oil is far higher than its cost of production and distribution as a result of the considerable productivity disparities between the different deposits. But these markets function in a very imperfect way. The first lever for correctly pricing fossil energy is therefore to improve the functioning of energy markets.

The financialization of energy markets is often singled out as being responsible for wild fluctuations that make prices unreadable. Evading most regulations, spot markets often prove to be much more opaque than futures markets. The regulatory effort therefore should be focussed on these spot markets as a priority, which calls for new information on the conditions of physical supply and demand, which are often deliberately kept opaque. Another distortion of the pricing of the scarcity of fossil fuels is the practice of subsidies for social or economic reasons (e.g. retail prices of gasoline in Iran or Indonesia or subsidies for coal in Germany and peat in Ireland). The IEA estimates that this type of subsidy amounts to more than 409 billion dollars worldwide, which represents around twice total government support for the development of renewable energy. Correct information as to the scarcity of fossil energy requires that these subsidies should be ended or replaced by other means of intervention. The setting up of sovereign funds designed to reallocate oil and gas rent toward economically and socially useful long-term uses is one way of acting in this direction. Their development in various oil-producing countries could be a lever for financing green growth.

But a second scarcity must be taken into consideration: the atmosphere's capacity to absorb greenhouse gas emissions. Among the seven "planetary boundaries" identified in the first section, climate change plays a specific role. It is the system whose deterioration is likely to have the greatest impact on other natural regulatory systems: biodiversity, the water cycle, land use. If we take climate risk into account, the rate and forms of the energy transition must be completely changed. The stock of fossil fuels underground harbours much more carbon than can be absorbed by the atmosphere. Basing the energy transition solely on Ricardian rent in the traditional energy markets leads to a prolongation of the extraction of the stock. It is therefore necessary to embed the energy transition within a wider transformation toward a low-carbon economy. A second price should consequently be introduced and rapidly become the main one: the price of the right to emit greenhouse gases into the atmosphere, that we shall call the carbon price or value (Delbosc & De Perthuis, 2012).

Since the signing of the climate convention at the 1992 Rio summit, the introduction of a price on carbon in economic life has been frequently discussed within the framework of international negotiation and has led to the development of numerous pilot schemes: the Kyoto protocol's economic mechanisms, the introduction of carbon taxes in the countries of northern Europe, allowances markets in Europe, some U.S. states, Australia and New Zealand, and before long in Korea and China (Jouvet & De Perthuis, 2011). The most successful prototype, the European emissions trading scheme (ETS), offers three main lessons on the introduction of a carbon price into the economy in order to enhance natural capital.

- The introduction of a carbon price alters the relative returns on the different activities, leading to a different orientation of the tools of production. In Europe, the carbon price resulted in emissions reductions of around a billion tonnes during the first two phases of the market (from 2005 to 2012). The respective profitability of coal, gas and renewable biomass in generating electricity is radically changed when the carbon price reaches a certain level.

- To produce its full effect, the carbon price must change the long-term expectations of firms investing in production or distribution facilities in place for several decades. This creates a credibility problem for the public authority in the long run in an environment in which decision-makers' political horizons are tending to shorten, particularly in crisis situations. This is why the implementation of ambitious climate policies calls for innovations in public governance both nationally and internationally.

- The advent of a carbon price in an economy immediately raises the question of income distribution. In France, the introduction of carbon pricing in the form of a "climate-energy contribution" in 2009 has run into a problem of distribution, and the entire public debate has focused on one issue: who pays and who benefits? In the European market, the rule of free allocation consisting of transferring the rent created by the carbon price to companies has led many actors to spend more time negotiating their allocation than seeking innovative ways of reducing emissions. The transition to auctions in the third stage clarifies issues of redistribution between countries and actors. Internationally, discussions in the UN are focusing largely on these distributional questions. In the conclave of climate negotiations, policy makers are talking very little about the climate and the planet: it's all about money!

In introducing a carbon price into the economy, and making the price of carbon the key energy transition variable, we must therefore control its distributional effects. This lesson goes beyond the strict framework of climate change: whether it concern the climate, biodiversity, the water cycle, the ozone layer or any other aspect of natural capital, the implementation of green growth involves dealing with complex questions of distribution.

New questions of distribution and equity

The inclusion of the value of natural capital in the economy affects the distribution of existing revenues, which raises questions of fairness. Trade-offs in this area may be explicit or implicit, but cannot hide a basic economic fact: there are winners and losers. These distributional aspects must be taken into account if there is to be a successful transition to green growth, as illustrated by three examples taken at the international level, at the national level and in the area of action to protect biodiversity.

Internationally, the difficulty of establishing global regulation of greenhouse gas emissions comes down to an easily representable issue of distribution. Uniform pricing of carbon at $20 per tonne with an egalitarian (i.e. equal per capita) distribution of emission rights would lead to massive revenue transfers from industrialized countries to developing countries: a global flow of about $200 billion per year, twice total official development aid (De Perthuis, 2011). With a contribution of $93 billion, the United States would be the main loser, while India would be the main beneficiary, with a gain of $110 billion. Such a system is overwhelmingly favoured by the developing countries, which would be ready to sign such an agreement immediately. Conversely, the rich countries want a distribution of emission rights reflecting historical levels, based on the so-called "grandfathering right" adopted in the context of the Kyoto Protocol. The next stages of the negotiations involve finding a compromise formula by 2015 that enables emerging countries to be incorporated into a system of shared commitment. In the absence of global agreement, different carbon prices will emerge, reflecting the specific conditions of the different regions committing themselves to climate policies. The key issue in relation to equity and efficiency will then be the type of links connecting these regions.

In contrast, the Montreal protocol, signed in 1987, managed within two decades to eliminate the Freon gas emissions causing the destruction of the ozone layer. Its success was based on establishing a standard banning the use of these gases, coupled with a subsidy mechanism to facilitate the conversion of plants located in developing countries. Two types of transfer underlay the spectacular success of this international action programme: an explicit financial transfer towards the countries of the global South; and an implicit transfer in favour of the U.S. company Dupont, which, after previously engaging in general lobbying calling into question the dangers inherent in the use of Freon gas, became one of the ardent supporters of the ban. The company was the first to develop an alternative technology and has been the main beneficiary of this new regulatory system.

The distributional effects of actions on behalf of the environment are found within each country. In France, there is a whole array of state intervention mechanisms, the distributional effects of which are poorly understood. Let us give some examples. Households investing in improving the energy efficiency of their homes receive tax deductions, which are sometimes very generous. As tax-paying homeowners, they would often be in a position to make these investments without such assistance. How can we measure the real effectiveness of such mechanisms, both in terms of efficiency and fairness? Another example: the progressive adoption of ambitious thermal standards is advocated by the three major French construction groups. There is no reason to doubt their commitment to the environment. But do these standards not risk accentuating the power imbalance within the sector between the three majors and the mass of small and medium-sized companies? A further assessment remains to be made, that of the distributional impact of repurchase tariffs for renewable power that are enjoyed by auto-producer households but which should in principle be passed on to all customers via an adjustment mechanism.

As well as closely examining all existing pro-environmental mechanisms, the implementation of green growth requires all countries to make explicit trade-offs in two areas: the price of fossil fuel paid by households and professional retraining. The phenomenon of "energy poverty" affects some 15-20% of households in western Europe and has grown rapidly since 2008. To implement energy transition with public support, it is necessary to combine price rises for fossil fuels with levers targeted at these households. In the short term, several possibilities can be studied, ranging from increasing pricing according to per capita electricity and gas consumption (the Californian model) to compensation targeted at the greening of taxation (as opposed to the undifferentiated "green cheque" technique). Clearly, green growth both creates new jobs and destroys old ones – jobs that were effectively predatory on natural capital and ill-adapted to the new economic system. The transition costs may prove to be very heavy in the absence of socially proactive retraining measures to ensure the fluidity of the labour market.

One area where subjective feelings seem sometimes to get the upper hand in decision-making is the protection of biodiversity. Our almost innate fondness for certain creatures makes us want to protect threatened migratory bird species, the polar bear and the giant panda so beloved of a major environmental organization! In reality, it is neither the birds nor bears that matter so much as the habitats and ecosystems that support them. Unlike climate change for which CO_2 has become the yardstick of a universal metric, it is nigh impossible to agree on a common unit of biodiversity, and harder still to put a price on it. Society nevertheless places a very high value on biodiversity in certain circumstances: the oil company BP found this out to its cost after the accident on the Deepwater Horizon oil rig in the Gulf of Mexico, the impact of which quickly overshadowed the fact that there were eleven human victims. But apart from such exceptional situations, how to put a figure on the protection of biodiversity remains unknown.

The threats to biodiversity come in many forms, as do the actions undertaken to preserve it. The most important vector on a global scale comes from changes in land use following the extension of agriculture and stock rearing (OECD 2012). The resulting pressure on natural habitats rich in biodiversity is not at all due to any wish on the part of farmers to destroy nature. Rather it stems from the growth in demand for food products deriving from the increasing population and changes in eating habits. The main conservation investment in the diversity of species is therefore to introduce economic incentives that make the use of biodiversity more profitable for agricultural production than its destruction. This emphasis opens up new fields to agronomic research and raises the question of distribution among the different social groups in competition for the use of these lands, as may be seen in developed countries with high density populations where peri-urban expansion is increasingly encroaching onto agricultural land (though forest and wetlands are generally better preserved). But it is in regard to tropical deforestation that this issue is most pronounced. The success of international negotiations on halting deforestation depends on the capacity of projects to prove themselves on the ground, where the enhancement of biodiversity can be made economically more viable, in particular by making use of the know-how of local communities, in order to increase the agricultural and food supply. Another illustration is the enactment of the new Brazilian forestry code, which is probably the most significant political decision in this respect anywhere in the world. It gives rise to a complex trade-off that President Rouseff must make, faced with a parliament sensitive to the influence of the ruralistas, advocates of strengthening Brazil's position among the great agrifood exporters, even if means sacrificing tens of millions of hectares of Amazonian forest and the communities it supports.

The levers of financing

In theory, once the value of natural capital is correctly incorporated into the production function, economic actors react spontaneously to changes in economic returns by redeploying their investments. In practice, the implementation of green growth entails a revision of the risk evaluation scale used within the financial system. This scale should be widened by better taking account of natural capital, and its temporal horizon extended.

Bank financing

Contrary to common belief, the deregulation of financial markets in no way reduced the role of banks in financing economies. The primary lever to activate for financing green growth is therefore bank lending. The strengthening of prudential rules applies to banks independently of the type of financing used. It consequently risks drying up the financing intended for the greening of growth. In order to mobilize the resources needed at the lowest possible interest rates, it is advisable to set up mechanisms favouring the profitability of this financing category. Consider two examples: the renovation of the housing stock and the international financing of projects.

In all the world's banking systems, financing housing and property is the primary engine for distributing credit. From the bankruptcy of Kreditanstalt in Vienna in 1931 to the sub-prime crisis of 2008, it is, moreover, insolvency is this area that precipitates banking crises. Yet one of the investments most needed for energy transition is the conversion of property: currently accounting for 25-30% of CO_2 emissions, the property stock can become neutral or even net exporters of energy. If it is agreed to spread out the transition over more than 100 years, it is sufficient to tackle new building by setting ambitious thermal standards and ensuring these are adhered to through additional supply and demand for housing. The problem is then financing the additional cost of around 10-20% per new dwelling without reducing economic activity, which will happen automatically in the absence of adequate financial incentives. Inclusion of the renovation of the old housing stock complicates the picture, since the costs of bringing the housing up to the required standard are high and vary from one building to the next. In both cases, the banking system cannot spontaneously provide this type of financing, for which returns on the investment are often counted in decades. Hence the need to find the right levers to reduce interest rates on loans of this kind. An interesting innovation in this area has been made in the United Kingdom within the framework of the Green Investment Bank, a new state-owned bank, one of whose primary aims is to facilitate the energy renovation of housing by guaranteeing loans for future energy and CO_2 emissions economies.

Energy infrastructures are one of the main segments addressed by international banks' financing projects. The "greening" of this business can firstly be facilitated through the use of standards. The "Ecuador principles" decreed in collaboration with the World Bank opened the way in 2003. The Climate Bonds Initiative tries to introduce such a standard for all issuance of bonds intended to finance the transition to a low carbon economy. In both cases it is difficult to determine whether these standards allow green financing costs to be reduced by attracting more capital. A far more important lever is the possibility introduced in the wake of the Kyoto Protocol of directly increasing the value on an allowances market of emissions reductions obtained through projects. When the price of CO_2 reaches 15 dollars per tonne, these revenues can account for up to 20% of the revenue from energy efficiency or renewable energy projects, by sharply increasing their financial yields. Strengthening the pricing of carbon would allow the effect to be considerably leveraged.

Conservation and compensation investments

Wisely used, carbon prices could also contribute to the investment needed for conserving biodiversity. Faced with the risk of major loss of biodiversity, the first measures taken have been of a regulatory kind: the creation of protected natural areas, under the aegis of the public authorities (for example, the Natura 2000 areas in Europe). While relatively effective in the developed countries, these methods have yet to be put into practice in many developing countries. They need to be combined with instruments encouraging local populations to increase the value of the services that the preservation of ecosystems can bring.

The protection of tropical forest is one of the most reliable ways of achieving this, while at the same time avoiding emissions in the order of 6-8 billion tonnes of CO_2 a year. If a price of 15 dollars for each tonne of emissions avoided could be achieved, it would represent some 100 billion dollars, or the amount that the industrialized countries agreed to transfer to the countries of the global South at the Copenhagen conference. Here too, the carbon price could have a major leverage effect, relaying the efforts made on a much smaller scale by the World Bank and the Norwegian government. This whole area has become a major focus in climate negotiations.

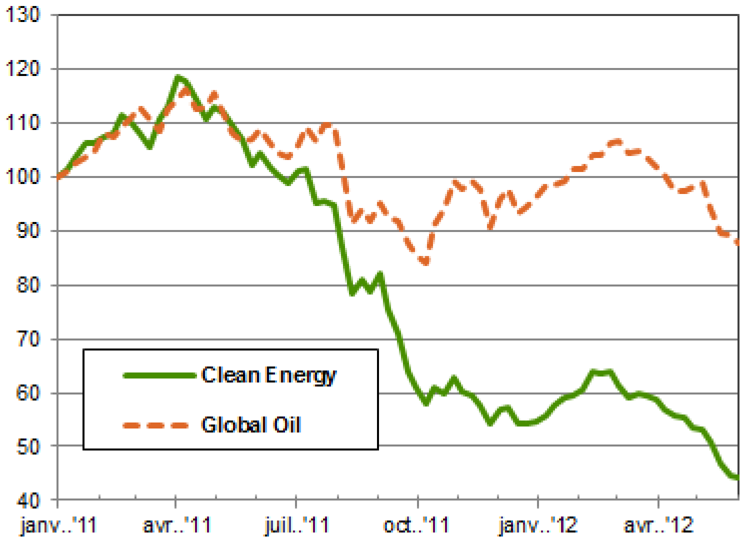
Another way of investing in biodiversity is to set up compensation systems taking a standard biodiversity unit as a yardstick. These mechanisms, introduced with the development of Mitigation Banks in the 1980s in the United States, have attracted investments worldwide in the order of 3-4 billion dollars. In France, the Caisse des Dépôts launched a compensation programme in 2010 that began applying the obligation deriving from a 1976 law to compensate damage to biodiversity.

Long-term investors

Among the actors likely to contribute most to changing the financial system, mention should be made of long-term investors such as sovereign funds, pension funds, life insurance companies, etc. These actors all mobilize substantial assets within a long-term profitability horizon and constraints spread out over time in terms of liabilities. Some of these, like the Norwegian oil funds, have already instigated a portfolio allocation strategy explicitly oriented towards energy transition and investment in biodiversity.

Taken together, these actors have considerable weight: if they were to move their capital toward the most innovative companies in terms of green growth, there is little doubt that the scale of financial yields among market values would be significantly altered. Despite the determination of some actors, we are still a long way from this situation, as is shown, for example, by the change in New York stock exchange prices, which between January 2011 and May 2012 gave a 40% overvaluation to oil companies as against companies committed to renewable energy. The mitigation of climate risk is still poorly valued on Wall Street from the standpoint of the immediate profits generated by shale gas.

Graph 2: comparative stock market prices of energy companies
(Standard & Poor's – World index)



Source: New Energy (reproduced with the permission of *Energy Intelligence*)

Public funding

It is out of the question to address financing issues without referring to the role of states. At the peak of the euphoria reigning during the creation of the speculative bubble, it was fashionable to minimize the role of these outmoded actors. Encouraging green growth calls for a redeployment of public funding in the area of infrastructures and R&D.

The organization of urban and rural areas is shaped long in advance by decisions regarding municipal infrastructure, particularly transport systems. Even though users and private capital may contribute to the financing of some systems, the role of government remains decisive in all cases. In this respect, green growth calls for new trade-offs, that are often difficult to make. In countries such as Brazil and Indonesia, the opening up of new communication routes in primary forests is a vector that greatly increases the pressure on ecosystems, but may bring other short-term benefits. Making the right choices involves placing sufficient value on the services provided by the ecosystems and requires a degree of political will. In France, a number of commissions have successively lowered the discount rate used by the public authorities and incorporated a carbon price increasing over time in order to alter public investment choices. But this has not yet stimulated investment in favour of rail freight, which moreover is generally agreed to be necessary.

Governments are also expected to provide intangible investment support in the form of support for R&D. Green growth calls for a speeding-up of innovation to bring about a broader conception of efficiency. Green growth is far more technical than traditional growth. In Europe, few countries have the means to increase their efforts in this area apart from Germany, which has resolutely followed this route for ten years in relation to energy efficiency. In France, strengthening government support for R&D could go hand in hand with a greening of taxation. Simulations undertaken by the working group on the transition to a low-carbon economy reveal that the most appropriate way of recycling a carbon tax would be to allocate two thirds to reducing expenditure and one third to stimulating R&D

(Centre d'Analyse Stratégique, 2011). According to simulations carried out with the help of the French treasury's macroeconomic model, this would lead to the net creation from the second year of some 100,000 jobs by 2020. Practical studies have still to be conducted to confirm the relevance of these simulations.

Conclusion

Our analysis is mainly concerned with showing that it is possible even in the short term to activate the levers of green growth. This historical, theoretical and practical analysis leads us to rethink society's modes of production by including the returns engendered by the environment in decision-making. Attempts to maintain growth on the basis of technical advances as a sole response to the depletion of resources or pollution in fact results only in an accelerated deterioration of environmental regulatory functions and puts at risk the very conditions for renewing traditional factors of production. It is for this reason that the energy transition must immediately incorporate carbon pricing in order to protect the natural regulatory capacity of the climate.

In our contemporary economies, without waiting for a complete change in behaviour or generalized pricing of natural capital, we can nevertheless give impetus to a green growth dynamic. Doing so mainly involves gradually incorporating the value of the environment into decision-making and taking account of the resulting redistribution phenomena. There is in principle no ineluctable conflict between efficiency and equity. Finding the right return on factors of production (economic efficiency) can lead to the implementation of a redistribution policy (social equity).

While we can already perceive the conditions for green growth, we still need to study, within production sectors, the real possibilities and orientations to adopt for this growth to be maximally beneficial in the short, medium and long term. To achieve this, we must identify the technical and organizational innovations that generate efficiency gains for all resources and we must construct financing methods allowing these innovations to be disseminated as quickly as possible.

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Technical Appendix

Here we model all the interactions between the environment (environmental quality, emissions, pollution stock) and production. This allows us to highlight 1) the productivity share of physical capital and human capital attributable to emissions, 2) the role of environmental quality in production and 3) the cumulative effects of pollution.

A1. **The Technologies**

The production function in period *t* is written:

$Y_t = B_t\, F(K_t,H_t)$

With K_t for physical capital and H_t for human capital. By mixing the classical endogenous growth models, A (Q_t) and the technology element as Stokey (1998), we have:

$B_t = zA(Q_t)$

with Q_t for the environmental quality, $A'(Q_t) > 0, A(0) = 0$ *and* z is an index of technological use, z between 0 and 1. Pollution per unit of production is an increasing function of z. The production function is then defined by:

$Y_t{=}z\, A(Q_t)\, F(K_t,H_t)$

We can define a pollution index as the ratio between emissions and production:

$I\,(z) = E_t/A(Q_t)\, F(K_t,H_t)$

We assume that I (.) is a bijective function increasing, convex and satisfying: $I\,(0) = 0, I\,(.)> 0$ *and* $I''\,(.)> 0.$

Note if z <1 then the model is equivalent to a production function of three factors including the flow of pollution E_t. We obtain this function by eliminating z between the above equations.

$Y_t = I^{-1}\,(E_t/(A(Q_t)F(K_t,H_t)))\, A(Q_t)\, F(K_t,H_t)= G(K_t,H_t,E_t, Q_t).$

Note: E_t can be interpreted as a level of extraction of an exhaustible resource (like hydrocarbon) or include the use of polluting exhaustible resources if we have an unequivocal link between the resource and emissions. In this case, we only have to replace the level of extraction by the relationship with E_t and we get a production function with three factors without making a detour through a function including directly an exhaustible resource.

An index of environmental quality at the time *t* can be defined by the quality of the pollution-free environment, Q_0 and by the inventory of pollution accumulated until that date, P_t. The pollution stock at the date *t* is given by a combination of accumulated past stocks, P_{t-1},, and the emission stream, E_t.. This allows us to consider the feedback of the flow of pollution on environmental quality and thus on the production possibilities, $Qt = Q\,(Pt, Et)$.

In this case, the production becomes,

$Y_t = A(Q_t\,(P_t,E_t))\, F(K,H,E)$

We can then reason in terms of pollution as well as in terms of environmental quality. Investing in depollution, however, means reducing the factors limiting growth while investing in environmental quality can increase potential growth.

A2. The Cobb-Douglas case

Production function: $Y_t = A_t K_t^{\alpha} H_t^{\beta}$,

Pollution index: $I(z) = z^{1+\gamma}$

When substituting z between the two relationships, we obtain:

$Y_t = A_t^{\gamma/1+\gamma} K_t^{\alpha\gamma/1+\gamma} H_t^{\beta\gamma/1+\gamma} E_t^{1/1+\gamma}$

Considering that environmental quality is a function $A(Q_t) = A(Q(P_t)) = (Q_0/P_t)^{\theta}$ and that $P_t = P_0^{(1-\lambda)} E_t^{\mu}$, avec λ, a natural rate of pollution absorption between 0 and 1, and μ the part of emissions flux contributing to the increase of pollution stock, then we obtain :

$Y_t = Q_0^{\theta\gamma/1+\gamma} P_0^{-\theta(1-\lambda)/1+\gamma} K_t^{\alpha\gamma/1+\gamma} H_t^{\beta\gamma/1+\gamma} E_t^{(1-\theta\mu\gamma)/1+\gamma}$.

So if we allow pollution to increase, the environmental quality tends to zero and the possibilities of production, $A(0) = 0$ also. We obtain a complete description of the production, taking into account all interactions with the environment.

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