Explaining neoclassical economists’ pro-growth agenda: does the popular Solow growth model bias economic analysis?

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Abstract: The Solow model concludes that long-run growth depends on technological progress, which is taken by neoclassical economists as suggesting there are no limits to growth because humanity’s capacity to think and expand knowledge is unlimited. This paper develops a two-sector Solow model consisting of natural and economic sectors, and it demonstrates that continued rapid growth is not inevitable and an economic collapse is possible. The logical application of the Solow model thus does not provide a justification for continuing the energy-based technological change and economic growth we have experienced over the past two centuries.

Keywords: environment; growth collapse; neoclassical model; Solow model; economic growth.


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“[T]he macroeconomy is not the relevant whole, but is itself a subsystem, a part of the ecosystem, the larger economy of nature.” (Daly, 1998)

“[H]umanity’s demand on the planet’s living resources...now exceeds the planet’s regenerative capacity by about 30 percent.” [World Wildlife Fund, (2008), p.2]

1 Introduction

Solow’s (1956) neoclassical model of economic growth concludes that economic growth can be sustained only if technological progress continues to offset diminishing returns to investment. Because the Solow model predicts that the economy falls into a zero-growth steady state when there is no technological progress, it is taken by many neoclassical economists as proof that the unprecedented economic growth of the past 200 years was the result of an exceptional acceleration of innovation and technological change.

According to historical estimates of per capita real GDP, human ingenuity indeed seems to have triumphed over diminishing returns. It is safe to say that most economists, social scientists, political leaders, and almost everyone else in the developed world now views increasing incomes (and consumption) as the new normal. If questioned why growth should continue indefinitely, many economists refer to the Solow model’s conclusion that long-run growth depends on technological progress and then argue that there is no obvious limit to humanity’s capacity to think, learn, and expand knowledge.

Growth economists have supplemented the Solow model with models of technological change (e.g., Romer, 1990; Aghion and Howitt, 1998); and interestingly, such models are based on Schumpeter’s (1934) dynamic model of creative destruction that generates technological change in an economy characterised by imperfect competition and excess profit. This departure from the neoclassical paradigm leads us to suspect that economists’ acceptance of economic growth as ‘the normal state of affairs’ may be more ideology than a rigorous application of the neoclassical Solow model.

Not everyone is as optimistic about future economic growth. For example, the journalist Richard Tomkins suggests that some skepticism may be in order:

“In the industrialized west, we assume that the ‘normal’ rate of economic growth is 2–3 per cent a year because it is what we have experienced in our lifetimes. For most of human history, however, ‘normal’ – in terms of per capita growth – has meant more or less zero.” (Tomkins, 2003)

Is Tomkins contesting our faith in human ingenuity? Or is he implying that the Solow model should not be construed as suggesting that future economic growth is simply a matter of continuing the past 200 years of technological progress?

This paper seeks to answer these questions. This paper will not address the various alternative approaches and critiques of the Solow model, such as its aggregation of capital (Kalecki, 1971; Blanchard, 1986); the absence of demand-side effects (Harrod, 1937; Robinson, 1956; Kalecki, 1971); the omission of human capital (Nelson and Phelps, 1966); its inability to address distributional issues within its aggregate framework (Robinson, 1956; Kaldor, 1956); or its unrealistic assumption of technological change as a constant and stable process (Nelson and Winter, 1982). Rather, this paper seeks to show that the popular Solow model, regardless of its accuracy, cannot be logically interpreted by neoclassical economists as providing support for the pro-growth agenda of
mainstream economics. A simple extension of the Solow model clearly reveals both the exceptional nature of past technological change and the difficulties humanity faces in continuing the energy intensive twentieth-century economic growth.

The Solow model as it is commonly taught in neoclassical textbooks is a single-sector model that covers only the narrow segment of human activity measured by GDP; but, the economic sector uses many inputs that come from nature, or what some refer to as the natural sector of human activity. For example, the last 200 years of technological change has greatly increased the use of exhaustible resources and carbon energy, where the use of the latter now threatens the natural ecosystem’s capacity to supply renewable services. Climate change is perhaps the most obvious outcome of humanity’s destruction of the ecosystem. Because the capacity of the ecosystem is limited, it constitutes a source of diminishing returns in the economic sector. A two-sector Solow model consisting of natural and economic sectors clearly shows that economic growth can continue into the future only if there is continual broad-based technological change across both sectors. But, if capitalism and its closely allied political systems continue to offer incentives only for technological change in the economic sector, the past 200 years will indeed prove to have been an anomaly and not the start of a new era in which economic growth is the normal.

This finding is intriguing because it suggests that mainstream economists’ optimism about long-run economic growth is not necessarily based on the Solow model. Just as ideology has driven the widespread embrace of Schumpeter’s dynamic model of creative destruction to explain technological change, the same underlying pro-growth ideology is restricting the logical extensions of the neoclassical Solow model.

2 Accounting for the natural environment

Neoclassical models almost invariably limit their analysis to purely economic variables, while being reductionist and ignoring many salient linkages between economic variables. Daly (1998) argues that neoclassical economics takes too narrow a perspective of economic activity, and he suggests that the economy should be analysed as embedded within the natural environment. When humans were hunters and gatherers, they were cognizant that they derived their existence directly from nature. Today, humanity depends more than ever on natural resources and services, but the high degree of industrialisation and urbanisation has separated most people from direct contact with nature. Our food comes from boxes and cans purchased in a supermarket, and gasoline squirts out of a gas station pump. Economic models have reinforced this loss of perspective by severing the connections between economic activity and nature.

Costanza et al. (1997) estimated that in 1997 the annual median value of renewable resources provided by our natural environment was $33 trillion. Since global GDP for 1997 was about $18 trillion, this means that the ecosystem, that is, the climate, fresh water, heat, air, land, soil replenishment, pollination, waste recycling, etc., is worth more to humans than the output currently attributed to human production. In response to the Costanza et al. study, numerous estimates of the value of specific components of the biosystem have been generated, accompanied by a wide-ranging discussion over whether accurate monetary estimates of the economic value of nature are even possible. Nevertheless, there is general agreement that the value, however defined, of nature’s services is very large and generally ignored in mainstream economic analysis.
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Humanity has always helped itself to the Earth’s available resources. Hunters and gatherers may have worshiped the Earth, but they had no qualms about taking what they needed for their survival. Over the past 10,000 years, with the development of agriculture and urbanisation, humanity has been hunting and gathering in more indirect ways. The growth of human population and the increases in material production permitted by the indirect use of nature’s resources have, especially since the Industrial Revolution, accelerated the rate of exploitation of nature. Today, Earth’s ecosystem is under severe pressure from the past and present growth of the human population and economic activity.

Wackernagel et al. (2002) estimated that humanity’s exploitation of Earth’s resources grew from 70% of capacity in 1961 to 120% in 1999. In a more recent assessment, the World Wildlife Fund (2008) estimated humanity’s global ecological footprint in terms of global hectares (gha), defined as the average capacity of one hectare of the planet’s surface to produce services and absorb waste. Summing across all forest, grazing land, cropland, and fishing grounds required to produce the food, fibre, and timber humanity consumes; the land and water needed to absorb the wastes emitted when humans use energy; the land and water required for humanity’s living space, production, transportation, and storage, the total productive area of the earth was equal to 13.6 billion gha, or 2.1 gha per person in 2005. In that year, however, the global ecological footprint was estimated to be 17.5 billion gha, or 2.7 gha per person, which implies “humanity’s demand on the planet’s living resources . . . now exceeds the planet’s regenerative capacity by about 30 percent” [World Wildlife Fund, (2008), p.2]. Some time during the 1980s, the human population began using nature’s services at a rate that exceeded the capacity of Earth’s ecosystem to supply them.

At the same time, Earth’s stocks of non-renewable resources are being depleted rapidly. Such exploitation per se need not be catastrophic: Baumol et al. (1989) explain that the effective stocks of resources can be maintained if technological progress increases the efficiency with which resources are converted into final goods faster than the actual physical resources are used up. However, technological advances are not sustaining the effective stocks of all non-renewable natural resources. For example, evidence on the increasing costs of finding and extracting petroleum suggests that humanity is approaching ‘peak extraction’, and additional supplies of crude oil will prove increasingly difficult to exploit. Technological progress can make new energy sources available, but, to date, the private sector of the economic sector has developed few viable alternatives to petroleum and other carbon-based fuels. Meanwhile, the world’s fastest growing emerging economies, including Brazil, China, India, and Russia, are building infrastructures that will rapidly increase the use of carbon energy.

3 Two daunting environmental problems

Humanity’s social and economic institutions are not constructed to induce investors, producers, and consumers to take full account of what happens in the natural sector. Humans are failing to make the investments in conservation to prevent a decline in the ecosystem’s capacity to provide its goods and services; nor are they generating enough new ideas, knowledge, and technologies that increase the efficiency with which the economies of the world transform natural resources and nature’s services into welfare-
enhancing products. The growth of economic output by the growing number of humans on Earth is causing two especially difficult environmental problems: global warming and the loss of biodiversity.

3.1 Global warming

There is broad consensus among scientists that Earth’s atmosphere is warming and that this warming is caused by human economic activity, mostly in the form of greenhouse gas emissions by industry, transport, power generation, and agricultural production. There is still uncertainty, however, over the extent, scope, and consequences of global warming, although nearly all scientists agree that a continuation of current trends in the growth of greenhouse gas emissions will most likely substantially affect life on Earth over the next century (Balmford and Bond, 2005; Intergovernmental Panel on Climate Change, 2007). Stern (2008, p.1) describes global warming as follows:

“Greenhouse gas emissions are externalities and represent the biggest market failure the world has seen. We all produce emissions, people around the world are already suffering from past emissions, and current emissions will have potentially catastrophic impacts in the future. Thus, these emissions are not ordinary, localized externalities. Risk on a global scale is at the core of the issue.”

Secondary effects from the warming of the atmosphere include rising ocean levels because of the melting of ice in the Arctic, Antarctic, and mountain glaciers; entire countries, such as Bangladesh and the Netherlands, could be submerged. There is further uncertainty about potential delayed feedback effects from an initial increase in temperature, such as the possibility that rising ocean and soil temperatures, especially in the Arctic, will release large amounts of GHGs stored on the ocean bottom and in the permafrost that will then trigger an exponential rise in global warming beyond anything experienced at least during the last 70 million years.³

Humanity’s response to the potentially disastrous consequences of global warming has been hampered by the special characteristics of the process of global warming. First, global warming is a very slow process: recent rises in atmospheric temperatures result from GHGs emitted over the past two centuries, mostly after World War II. The slow reaction of the climate to GHG accumulation also means that current GHG emissions will not have a noticeable effect in atmospheric temperatures for many years. This constitutes a problem of inter-generational externalities. It is psychologically difficult to respond to something that cannot be seen or felt but must be perceived abstractly.

Second, global warming is a delayed process that will not stop, much less reverse itself, for decades even if humans were to drastically cut GHG emissions today. So humanity faces consequences from current GHG emissions that will not become apparent for many years. Yet, if policymakers wait until everyone notices the climate changes they are now setting in motion, it will, most likely, be too late to reverse the process.

3.2 The loss of biodiversity

Biodiversity refers to the number of different species of plants, animals, and micro-organisms that exist on earth as well as the genetic variations and traits within species and the assemblage of these species within ecosystems. The rate of species extinction has accelerated precipitously over the past century, caused largely by the
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growth of the human population and its per capita economic production. As humans occupy more space and exploits more of nature’s resources and services, there is less space for other animals and plants. Diverse natural forests, grasslands, and wetlands have been replaced by monoculture, and today most of the world grows the same small number of varieties of corn, wheat, rice, fruits, and vegetables; and also raises the same species of cows, pigs, chickens, and sheep.

The gain in agricultural efficiency from monoculture and carbon-intensive mechanisation – known as the green revolution – has been credited for humanity’s ability to avoid starvation despite the growth of world population from 2.5 billion in 1950 to just over 7 billion today. However, there is growing evidence that monoculture does not necessarily increase efficiency (Rosset, 1999; Pacini et al., 2003; Gül, 2008; Rodale Institute, 2011). And, the widespread use of pesticides during the green revolution has adversely human health, while unintentionally killing off numerous species (e.g., Spiroux de Vendômois et al., 2009; Stokstad, 2012; Whitehorn et al., 2012). The well-known example of the Irish potato famine in the 19th century suggests that monoculture has made human existence more risky. New technologies like genetic engineering and cloning may make animal species so nearly identical across the world that one type of new bacteria or virus could wipe out a huge portion of the world’s meat or dairy products (Monbiot, 2000; LaSalle et al., 2008; Gurian-Sherman, 2009; Séralini et al., 2011).

4 The Solow growth model and renewable resources

Despite its limitations and shortcomings, Solow’s (1956, 1957) growth model is still the central model in nearly all economics textbooks that cover economic growth. The Solow model incorporates the marginalist thinking of neoclassical economics, while assuming as ‘exogenous’ many variables that are, in reality, continually evolving in the complex and dynamic process of economic growth and change. Most notably, it takes the rate of technological change as given. The model does endogenise some of the main components of the growth process, however. For example, it shows that an economy can increase its output by:

1. increasing its stock of productive factors, or

2. improving the efficiency with which factors can be combined to produce output.

It also shows that there are fundamental differences between economic growth generated by factor accumulation and technological progress, with only the latter capable of sustaining growth indefinitely.

The textbook model usually begins with a simple aggregate economy-wide production function, \( Y = f(K, L) \), in which \( Y \) is total output, \( K \) is the economy’s stock of capital, \( L \) is the number of workers, and the function \( f(. . .) \) represents the economy’s state of technology. Solow also assumes that there are diminishing returns to individual inputs. The production function can then be written simply as \( f(K) \), with labour and other fixed factors pushed to the background.

Solow also argued that capital depreciates, and the larger the capital stock, the greater the amount of society’s savings that needs to be allocated to replacing or repairing the
capital stock. Solow assumed that depreciation is a constant fraction, $\delta$, of the stock of capital, $K$.\textsuperscript{4} In this case, the change in the annual capital stock, denoted as $\Delta K$, equals the difference between total new investment, $I$, which is equal to the savings rate, $\sigma$, times the level of income, and the amount of existing capital that depreciates, or:

$$\Delta K = I - \delta K = \sigma f(K) - \delta K.$$  \hfill (1)

When investment is greater than what is needed to replace that portion of the capital stock that wears out, $K$ and total output $Y = f(K)$ increase; if, however, total investment in new capital is not large enough to replace the capital that depreciates, $K$ and $Y = f(K)$ decrease.

In most undergraduate textbooks, the Solow model is shown graphically in a diagram with axes representing capital stock and total output. With output subject to diminishing returns to capital (other inputs like labour are constant), the production function slopes upward at a decreasing rate. With a constant savings rate, the investment function $I = \sigma f(K)$ is thus a diminished version of the production function $f(K)$, and its slope also decreases as the capital stock $K$ becomes larger. A constant rate of depreciation implies that the depreciation function is a straight-line function of capital, $\delta K$. Figure 1 combines all three functions.

\textbf{Figure 1} The Solow equilibrium

The Solow model concludes that, given the economy’s production function, savings rate, and depreciation rate, the economy’s capital stock adjusts toward the stable equilibrium level $K^*$ because investment exactly equals depreciation at the point $a$. To the left of $K^*$, the investment curve $\sigma f(K)$ lies above the depreciation line $\delta K$, and thus the capital stock grows towards $K^*$. To the right of $K^*$, the situation is reversed: depreciation exceeds investment, and the capital stock $K$ shrinks back toward $K^*$. Solow called this stable equilibrium level of the capital stock, and corresponding level of output at point $b$, the economy’s steady state equilibrium.
4.1 Nature as a source of diminishing returns

The Solow growth model effectively gives us only a partial view of the economy’s aggregate production function, that part of the model in the capital – output plane. There are, in fact, many other productive variables that enter the economy’s aggregate production function. For example, natural resources are inputs in most productive economic processes, and if they cannot be expanded, diminishing returns to other productive factors will occur.

The Solow model in Figure 1 is only a partial representation of our world. We instead follow Daly’s (1998) suggestion and build a neoclassical Solow-like model with both economic and natural sectors, the latter consisting of an ecosystem that provides renewable services or exhaustible resources. Because the Solow model must be modified differently for renewable and exhaustible resources, we treat each case separately. First we take up renewable resources.5

Suppose that the economy can be represented by the function:

\[ Y = f(K \cdot E_K, S \cdot E_S) \]

in which output is produced using capital, \(K\), and renewable resources, \(S\). As before, we hold the constant labour force in the background.6 \(E_K\) and \(E_S\) represent factor specific technologies, so that the production function shows the effective stock of physical capital and nature’s effective capacity to generate the many services that are inputs in human production and critical contributors to human life. The effective supply of a resource is equal to the ultimate benefit its use in production yields, so that an improvement in technology would increase the effective stock of an input. As in the case of the simple Solow model above, if one of the inputs is fixed in quantity, then the other inputs are assumed to be subject to diminishing returns.

This two-sector version of the Solow model could be shown in a three dimensional diagram, but given the difficulties of drawing a three-dimensional diagram on a two-dimensional sheet of paper, it is actually easier to break it into two parts, each consisting of two dimensions, and placing the two side-by-side. In the natural sector of the model, output \(Y\) is related to the amount of nature’s renewable services \(S\). The Solow model’s traditional economic sector is where output \(Y\) is related to the stock of physical capital \(K\). Both physical capital and the ecosystem are subject to depreciation. But, the depreciation function in the ecosystem is not linear. The services that the ecosystem provides are gradually replenished after humans make use of them. Therefore, nature’s services are limited by nature’s capacity to replenish.

Examples of the relationship between usage of nature’s services and nature’s capacity to supply renewable services include humanity’s \(CO_2\) emissions. If emissions exceed the natural system’s capacity to dissipate them, then the atmospheric temperatures rise and the services provided by the natural climate no longer conform as closely to the needs of Earth’s living organisms, many of which are critical for human existence and production. Hence, overall costs rise in the economic sector. Similarly, if human production uses water faster than natural processes replenish it, less water becomes available for human use. A notable example is the shrinking of the Aral Sea in Central Asia to one third its original size after the Soviet Government’s irrigation projects to boost agricultural production diverted too much water. In general, the more intensively humans use renewable resources, the less likely nature is able to fully replenish itself.
In sum, humans can undertake conservation projects to restore nature’s capacity to provide its services, such as planting trees, leaving some percentage of agricultural land fallow, stocking rivers with fish, repairing shorelines and beaches, filtering waste water, using catalytic converters on automobile exhaust systems, etc. But, if humanity increasingly takes from nature without engaging in the necessary conservation efforts to sustain the ecosystem, the ecosystem’s capacity to provide services declines.

Figure 2 depicts the natural sector of human existence. The production function in the natural sector of the expanded two-sector Solow model is assumed to be subject to diminishing returns to nature’s services, \( S \). There is a ‘depreciation’ function, or more accurately, a conservation function, in recognition of the need to engage in explicit conservation activities when the ecosystem is destroyed.

Figure 2  Economic growth in the natural sphere (see online version for colours)

The conservation function is thus not linear like the depreciation function for physical capital in the economic sector. Nature’s capacity to provide its services may not be stressed at all at low levels of use. For example, in Figure 2, nature can increase its services from \( S_1 \) to \( S_2 \) at virtually zero marginal cost because nature fully replenishes the water, air, soil, etc. used in economic production. Thus, humanity can increase its output from \( Y_1 \) to \( Y_2 \) without incurring any long-run loss of nature’s services. However, when society increases its economic output to \( Y_3 \), there are noticeable stresses on the natural ecosystem. Conservation activities with an economic cost of \( c(S_3) > 0 \) are required to sustain such resource use. And, the near-vertical slope of the conservation function reflects the likelihood that once nature reaches such stress points, humanity cannot expand the use of its ongoing services much more before running into absolute limits. Another implication of the sharp upturn of conservation costs is that once nature’s capacity is approached, costs will soon grow much faster than the marginal gains in output, and further increases in production will no longer be welfare maximising.
4.2 A two-sector Solow model

Figure 3 presents an extended Solow model with the natural and economic sectors depicted side-by-side. Suppose technological change in the economic sector increases output from $Y_1$ to $Y_2$ by moving the economy to a new steady state that requires an increase in the capital stock from $K_1$ to $K_2$. Such an increase in economic output also requires increased inputs of natural services such as rainfall, oxygen, dissipation of air pollutants, absorption of water runoff, etc. We see that in the left-hand diagram, the rise in output requires no additional conservation costs because the ecosystem’s capacity has not been reached, and ample services of nature are forthcoming for economic output to rise to $Y_2$.

Suppose that innovation in the economic sector continues and the production function shifts to $f_2(K)$, which then could be expected to increase steady state output from $Y_2$ to $Y_3$ in the economic sector. Figure 4 shows that the rising conservation cost curve in the left-side diagram means that this further growth of economic output will have costly consequences.

Figure 4 shows that economic output $Y_3$ requires products and services from nature equal to $S_3$. To maintain this level of nature’s services, costly conservation efforts $c_3(S_3)$ are necessary; otherwise the higher use of resources will destroy some of nature’s capacity to provide its products and services and the conservation curve shifts to the left. Figure 5 illustrates what happens next: the decline in nature’s capacity to provide its renewable resources causes the production function in the economic sector to decline.

The decline in production in the economic sector will not be a one-time occurrence if economic decisions continue to ignore the consequences of economic production on the natural sector. The leftward shift of the conservation curve means that costly conservation activities are now required at levels of exploitation of nature’s services below $S_2$, the level of exploitation at which nature was formerly able to replenish itself without human help. And, unless society engages in real conservation activities in period 2, costing $c_4(S_2)$, further deterioration of nature’s capacity to provide water, air, warmth, carbon sinks, flood control, etc. will occur. A disturbing implication of this downward spiral of environmental deterioration is that the damage to the ecosystem becomes irreversible: with the conservation curve at $c_3(S)$, no amount of conservation can restore the ecosystem back to its initial capacity.

The likelihood that humanity will delay conservation is borne out by its failure to react to climate change and the loss of biodiversity. The slow reaction of nature to human exploitation delays humanity’s needed response, and economic collapse becomes inevitable. This scenario has occurred throughout history, as described by Diamond (2005).

Figure 5 also shows that the environmental devastation in the natural sector causes the production function in the economic sector to fall back to $f_2(K)$, and thus output falls back to $Y_2$. And, if the downward spiral described above is permitted to continue because society continues to ignore, or is incapable of responding to, the decline in the ecosystem’s production, output in the economic sector will also continue to fall, perhaps all the way back to $Y_1$ or beyond. If only humans had left ‘good enough’ alone and been satisfied with output $Y_2$!
Figure 3  Economic growth in the natural and economic sectors (see online version for colours)
Figure 4  Economic growth when the nature is stressed (see online version for colours)
Figure 5  From economic growth to economic decline (see online version for colours)
The important point is that the decline in nature’s productive capacity shifts down the production function in the economic sector. In neoclassical terms, the marginal product of one input depends on the supply of other inputs. Thus, the marginal product of an additional unit of physical capital in the economic sector declines when nature’s production declines.

We have thus reached some very interesting conclusions by:
1. expanding a one-sector neoclassical growth model to two-sector
2. allowing for delayed recognition and reaction times.

An intriguing question is why the model has not been applied more often in this manner.

5 Broader technological change

The two-sector Solow model suggests that when economic activity pressures the natural environment, the cost of maintaining nature’s production of renewable resources accelerates in non-linear fashion. At some level of economic output, the human footprint becomes large enough to do damage, which can be mitigated by means of costly conservation activities.

Of course, humanity could also choose to do things differently and find better technologies for producing what it needs. Figure 6 illustrates that if technological change had shifted nature’s production function from $f_1(S)$ to $f_2(S)$ in the natural sector when $f_2(K)$ shifted to $f_3(K)$ in the economic dimension, then output could have increased to $Y_3$ without requiring any additional use of nature’s services beyond its self-regulating sustainable level of $S_2$.

Technological change in the natural sector has, so far, been difficult to create and apply. Neoclassical analysis of economic growth would most likely suggest that the source of the difficulties is the lack of proper economic incentives. Indeed, the ecological costs of increasing output in the economic sector are seldom fully borne by those who make the economic decisions. Very few markets exist in the natural sector, and government regulation is spotty because business interests have largely used their economic power to prevent governments from using taxation or regulation to internalise the damage to the ecosystem.

Humanity has always found it difficult to deal with complex changes such as those suggested by the expanded Solow model. Diamond (2005) describes many failures of civilizations to deal with complex interactions of economic growth and environmental destruction throughout history. Today, the relationship between economic growth and environmental destruction is global, and the linkages between growth and nature are much more dispersed. Efforts to coordinate an international response to global warming have not yet been successful, as evidenced by the failure of recent negotiations to renew the Kyoto Protocol.
Figure 6  Technological change in both spheres (see online version for colours)
Figure 7  Economic growth with investment in the natural sphere (see online version for colours)
6 Yes, environmental costs will reduce economic growth

It is widely argued that environmental regulations, restrictions on carbon emissions, protection of endangered species, and other environmental regulations will slow economic growth. Indeed, the Intergovernmental Panel on Climate Change (2007) estimated it would cost between 1% and 2% of global GDP to reduce greenhouse gas emissions enough to avoid global warming; while Stern (2008) suggests the costs may be even higher. In 1999, a team of scientists from Cambridge and Sheffield Universities in the UK estimated that it would cost about 1% of global GDP to conserve the planet’s biodiversity (Houlder, 1999). The two-dimensional Solow model above supports such claims: policies to sustain growth across all sectors will result in slower output growth in the economic sector; but ignoring the natural sector will have much more costly consequences.

Figure 7 suggests a potential path of sustainable development. Suppose that, as in earlier examples, technological change shifts the production function to \( f_3(K) \) in the economic sector. To avoid the collapse of economic output described in Figure 5, some of the economy’s savings will have to be used to pay for innovation to shift nature’s production function from \( f_2(S) \) to \( f_4(S) \). Alternatively, savings could pay for conservation cost \( c_f(S) \). Of course, the diversion of savings lowers the savings/investment function in the economic sector, say to somewhere between \( \sigma f_2(K) \) and \( \sigma f_3(K) \), which reduces the increase in the steady state in the economic sector to something less that \( Y_3^* \). In short, environmental costs require GDP to grow more slowly, albeit sustainably. Long-run economic growth is, therefore, much more difficult than the simple one-sector Solow model suggests.

The growth of output in the economic sector without accounting for the costs of environmental destruction in the natural sector, as illustrated in Figure 6, effectively implies an unrecognised debt that will, eventually, come due. By not paying the cost of conserving the biosystem, nor paying for new technologies necessary to generate increased productivity in the natural sector, producers are merely pushing the costs forward until, like an unravelling Ponzi scheme, the runaway debt causes the system to collapse. The Solow model thus presents a choice between more near-term economic growth followed by an economic collapse on the one hand, and much slower but sustainable growth on the other.

7 Exhaustible resources

Technically, we have extended the Solow model to include nature’s renewable resources. Humanity also uses nature’s non-renewable, or exhaustible, resources such as coal, oil, copper, iron ore, gold, etc. Once used, the physical supply of these resources does not restore itself, at least not within a time frame relevant to human existence. Figure 8 shows the economy’s production function linking the use of exhaustible resources \( H \) to output \( Y \), ceteris paribus. There are no depreciation or investment functions because once used, exhaustible resources cannot be restored.
Baumol et al. (1989) show that output growth in the economic sector is sustainable only if technological change increases the output produced with each unit of exhaustible resources at least as fast as exhaustible resources are depleted so that the effective stocks of resources do not decline. In terms of Figure 8, output in the economic sector can increase only if the production function \( Y = f(H) \) shifts up and the use of actual physical inputs of the exhaustible resource \( N \) decline over time. Sustainable output growth from \( Y_1 \) to \( Y_2 \) to \( Y_3 \) requires technological change that shifts the production function from \( f_1(H) \) to \( f_2(H) \) to \( f_3(H) \). The physical inputs of exhaustible resources into the production processes in the economic sector must decline from, say, \( H_1 \) to \( H_2 \) to \( H_3 \).

Weitzman (1999) estimated the cost of resource depletion by assuming resource prices accurately reflect opportunity costs of effective alternatives plus extraction costs. Specifically, he concluded that use of the 14 most important exhaustible resources “causes us overall to lose the equivalent of about 1 percent of average consumption each year” [Weitzman, (1999), p.704], implying that exhaustible resources will run out unless resource-enhancing technological change is greater than 1% per year. Of course, Weitzman covers only 14 major minerals whose prices were easily available, so the real required rate of technological change is greater. Note also that exhaustible resource use also involves disposal costs (waste) and, as Krautkraemer (1998) notes, it also damages nature’s capacity to provide renewable resources.

Jevons (1864) noted another difficulty with improving the efficiency with which humanity uses nature’s exhaustible resources. He noticed that contemporary (and continuous) improvements in the efficiency of coal extraction led to increased use. Better mining methods lowered the costs of coal, and more efficient applications increased demand, so the use of coal grew. Technology’s positive effect on resource use came to be known as the Jevons effect. Khazzoom (1980) and Brookes (1990) applied Jevons’ ideas to energy in particular and offered a simple hypothesis: Energy efficiency gains result in increased energy use.

Saunders (1992) called this hypothesis the Khazzoom-Brookes postulate, with economic growth as the main mechanism. Efficiency gains make energy less expensive and increase its usefulness, and this stimulates economic growth, which, in turn, further increases energy demand. Evidence from the past 200 years supports this postulate. Today’s high levels of material consumption were made possible by technologies that
expanded use of carbon energy sources like coal and oil, as well as the oil-based chemistry that created the fertilisers and pesticides that increased agricultural productivity. Over the past 200 years, technological progress has clearly not reduced the use of natural resources as illustrated in Figure 8.

In accordance with the Khazzoom-Brookes postulate, the U.S. Energy Information Agency (2011) predicts world marketed energy consumption will grow by 53% from 2008 to 2035, largely because of the rapid economic growth of large developing economies like Brazil, China, and India. The extended Solow model suggests, however, that continued economic growth based on increased energy usage is not sustainable. Popp (2002, 2004) and Wackernagel and Rees (1996) therefore prescribe taxes and other mechanisms to raise resource prices in order to prevent technological advances from lowering the user cost of resources.

The estimated costs of maintaining nature’s services, dealing with global warming and the loss of biodiversity, and generating the technical progress to diminish the use of exhaustible resources is likely to exceed 4% or even 5% of global GDP. Given 2010 world GDP of just over $75 trillion, the costs of resource depletion would thus be more than $3 trillion per year, not an inconsequential amount. Not surprisingly, governments and their business constituency have been reluctant to incur these costs. But the expanded Solow model suggests that there is no alternative to recognising and paying for the real and full costs of economic growth.

Note that all of these conclusions have been reached following the basic logic of the neoclassical Solow growth model. This is an important point because it helps us answer the questions we posed at the start of this paper. The pro-growth bias of neoclassical analysis is not due to the predominance of neoclassical analysis. This is not to say that alternative paradigms would not further strengthen the case against continued economic growth. Georgescu-Roegen (1971), Daly (1998) and Jackson (2008), among many others, present strong arguments for why even slow economic growth may not be desirable or possible. But, nevertheless, a full logical expansion of the Solow model does not produce any justification for pursuing a continuation of the energy-based economic growth we have experienced over the past two centuries. Hence, there must be some other driving force behind the growth agenda of mainstream economics.

8 Conclusions and final comments

The extended Solow model that depicts both the economic and natural sectors of human existence suggests that sustainable growth in the economic sector requires humans to create and apply a broad set of technological changes that:

1. keep humanity’s use of nature’s services within levels that permit nature to maintain those services
2. increase the effective stocks of exhaustible resources so that actual physical consumption of resources can be reduced.

In other words, a logical application of the Solow model does not produce any justification for pursuing a continuation of the energy-based economic growth we have
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Experienced over the past two centuries. These conclusions nevertheless underestimate the formidable task ahead.

Studies that have analysed what must be done to stop global warming and the loss of bio-diversity, such as the Intergovernmental Panel on Climate Change (2007), Spratt et al. (2009) and Jackson (2008), show that the required new ‘technologies’ imply substantial changes to the way humanity has become accustomed to living, producing and consuming. Substantial economic and social changes solicit strong resistance not only by vested economic interests whose wealth depends directly on the continued free use of nature’s dwindling resources, but also by many others who prefer the status quo over unfamiliar new lifestyles.

The negotiations over who bears the adjustment costs for environmental problems such as global warming and biodiversity losses are further complicated by the need to use abstract models to anticipate uncertain future developments. Recall that these human-induced natural processes are slow-moving, and there is no quick feedback from policies to deal with these slow-moving environmental shifts. Abstract models can be easily disputed, and proof of their accuracy will not become available for decades. Innovation is itself an uncertain process, and future gains from innovative activity are equally difficult to predict at the time innovators are undertaking their research, experiments, tests, and applications.

These observations do not justify mainstream economics’ pro-growth bias, however. Economists should be comfortable with abstract models and slow-moving dynamic processes. After all, the economy is a dynamic process that can only be analysed using abstract models. But what then explains mainstream economics’ strong pro-growth bias?

The results from exploiting the neoclassical Solow growth model to its logical conclusions in a two-sector model suggest that it is not the Solow model, per se, that justifies economists’ strong pro-growth bias; rather, economics’ pro-growth bias can only be justified by an incomplete application of the Solow model, as in the case of the simple model that narrowly focuses only on market outcomes and technological change in the economic sector. That narrow perspective is a choice, not a logical necessity, which suggests that neoclassical economics’ pro-growth bias is fundamentally driven by ideology rather than by methodology. As the author of best-selling textbook on the history of economic thought, Robert Heilbroner, once remarked: “the best kept secret in economics is that economics is about the study of capitalism”. This suggests that economics is in need of a paradigm shift, not just a more diverse set of models. That is truly a daunting task. In the meantime, economists concerned about the environment should be able to make productive use of the finding that neoclassical economists’ favourite growth model can be used to make a case for more substantial environmental policies.

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References


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**Notes**

1 See World Resources Institute (2005) for a more thorough list of nature’s very long list of services.

2 Toman (1998) criticises Costanza et al. for, among other things, using the common methodology of estimating the value of some activity in terms of society’s willingness to accept compensation its loss. Toman argues that without nature we would all be dead, which suggests that Costanza et al.’s estimate is ‘a serious underestimate of infinity’. Farber et al. (2002) describe the diverse methods used in making these conjectural estimates.

3 The complexity of global warming is described by, among others, OECD (2002), Stern (2007) or the United Nations’ Intergovernmental Panel on Climate Change (2007).

4 There is no definitive evidence to suggest any one particular shape for the depreciation function. Unless new capital is very different from earlier forms of capital, it seems reasonable from a neoclassical modelling perspective to assume that depreciation increases when capital increases. More complex issues, such as the non-linear nature of diverse components of the capital stock, e.g., physical capital, human capital, and social capital, do not fit into the Solow model’s standard form. See DeGiorgio (1987) for an alternative perspective.

5 The categories of exhaustible and renewable resources are not entirely separable. Krautkraemer (1998) writes that nature’s capacity to provide services such as carbon sinks, clean water, and fertile soils is directly endangered by the pollution generated by the use of carbon fuels; conversely, the viability of exhaustible carbon fuels depends on nature’s ongoing capacity to absorb carbon.

6 We can make the same case for labour, human capital or any other variable, namely that the model should be expanded to take into consideration the source of all inputs used in the economic sector.

7 Quoted in Palley (1998, p.15). Dowd (2005) further explains the linkage between capitalism and economics pro-growth bias, and Harvey (2005) elaborates on the linkage between economics and the neoliberal paradigm that elevates economic growth to a moral cause.