Natural Capital, Sustainability and Productivity: An Exploration of the Linkages

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INTRODUCTION: THE ROLE OF NATURAL AND ENVIRONMENTAL RESOURCES IN THE CANADIAN ECONOMY

The goals of this paper are to explore potential relationships among natural capital, sustainability and productivity. Three questions are posed. First, how important is natural capital in sustaining natural resource production in the Canadian economy over time?[1] Second, does the omission of natural capital in estimates of productivity growth bias these estimates? And finally, has the role of natural capital changed over time as a result of three factors: its depletion, its degradation (declining quality) and technological change? Available data will be analysed with a view to providing an overview and suggested interpretation of what are very complex relationships. The paper begins by defining natural capital and discussing its link to sustainability. It presents trends in natural capital over the past 20 to 30 years. Links between natural capital and productivity are explored, focusing first on labour productivity and then on multifactor productivity of Canada's natural resource sectors. Next, the possible role of technological change in these sectors is examined, with specific examples for coal, copper, petroleum and forestry. The impact of omitting natural capital from productivity estimates is examined by looking at cases in which environmental resources are factored into the calculation. The paper concludes with observations on possible connections between productivity estimates and sustainability.

The economy's goods and services are produced with factor inputs, traditionally identified as land, labour and capital. Land has been a proxy for the stocks of natural resources — land and soils, timber, minerals, energy, water and the capacity of the natural environment to absorb or neutralize the waste products of production and consumption, protect organisms from excessive ultraviolet radiation, support ecosystem sustainability and much more. Economic modelling during much of the 20th century typically focused on the roles of labour and capital, implicitly assuming that natural and environmental resources were so abundant that they could be treated as "free" goods. Of course, most economists recognized that natural resources used as inputs were not free — capital and labour had to be used to extract or harvest them — but because of the relative abundance of natural resources they were routinely ignored in productivity studies and other aggregate analyses of the economy. It is typically when market or implicit prices of natural resources are particularly high — for example, during the "energy crisis" of the 1970s when petroleum prices skyrocketed — that natural resources enter into estimations of production functions and productivity.[2] The late 1960s and early 1970s also ushered in an awareness of the increasing scarcity of environmental resources, because pollution levels began to have a noticeable impact on human and ecosystem health.

The stock of natural and environmental resources is known as natural capital — capital in the sense that the resources are assets that yield services over time but can also depreciate. Depreciation of natural capital results from depletion and degradation (declining quality) of these stocks. Degradation may have a greater impact on production than depletion. When quality declines as a natural resource is extracted or harvested, the costs of extraction typically rise unless the decline is offset by technology. Data on quality are difficult to obtain and at the aggregate level would necessarily combine positive and negative quality changes. In this paper, quantity serves as an imperfect proxy for both attributes. Natural capital consists of three components: (1) natural resource capital — stocks of renewable and non-renewable resources, (2) ecosystems or environmental capital — systems that provide essential environmental goods and services, and (3) land — the space in which human activities take place. Measurement of Canada's natural capital has focused thus far on stocks of land, energy, mineral and timber.[3] The natural capital embodied in environmental resources is very difficult to conceptualize, let alone measure. However, even for the resources whose natural capital is more readily measurable, there is very little in the way of empirical estimation of natural capital's contribution to productivity. Research on how changes in the stocks of natural resources affect the sustainability of resource extraction or harvesting, and ultimately the sustainability of the economy, is limited but growing.[4]

Sustainability, broadly defined, is the ability of the economy to maintain the flow of production necessary to ensure non-decreasing per capita consumption indefinitely, so that future generations can have a standard of living equal to or better than that of present generations. To sustain production, the economy needs a constant supply of the inputs that are essential in the sense that without them there would be no output. The relationship between natural capital and sustainable output, then, depends on whether natural capital is essential — that is, the substitution possibilities between factor inputs. Some forms of natural capital, such as water and our atmosphere, are clearly essential. If the protective stratospheric ozone layer is lost, the amount of ultraviolet radiation reaching the earth's surface will be sufficient to exterminate most plant and animal life. Other types of natural capital — specific non-renewable or renewable resources (oil, timber) and even some of the waste assimilation processes of the natural environment — may not be essential. Natural gas, oil products extracted from tar sands or biofuels can be substituted for conventional oil in most uses. It is energy that is the key input in this case, not the specific type of energy input that is essential for production. Water and sewage treatment plants (reproduced capital) can substitute for the waste absorption capacity of rivers and lakes.

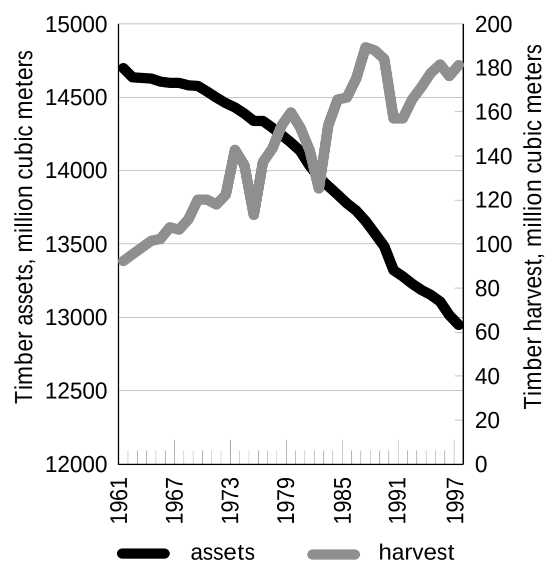
The concepts of weak and strong sustainability reflect the *essentialness* of natural capital to the economy and the environment. Weak sustainability means that an aggregate stock of capital (natural, human and reproduced) is maintained at a level necessary to ensure indefinite production. All of the forms of capital aggregated under weak sustainability must therefore be perfectly substitutable for each other. Strong sustainability means that specific forms of natural capital are essential (they do not have substitutes) and that stocks of these resources must be kept intact to ensure continued production. The challenge is to discover what forms of natural capital are essential and how to sustain the stocks necessary to ensure non-decreasing production, consumption and, hence, human survival. We do not have good estimates of how much natural capital we need. Our knowledge is particularly weak when it comes to understanding the complex roles of ecosystems in sustaining the hydrological cycle, climate, biodiversity, soil productivity and other natural processes. We also tend to look at forms of natural capital independently rather than as part of an integrated, multiple-input and -output system. Natural capital provides well-being directly to individuals along with yielding inputs used to produce other goods and services. Natural capital also occurs in the space where people live. Hence, its extraction or harvest affects people's quality of life, their employment, the long-term sustainability of their communities and their relationships with their ecosystems. Ideally, measurement of sustainability is directed to all the multiple uses of natural capital. This study is far more modest in scope. It explores linkages in aggregate and suggests many avenues for future work.

LONG-RUN TRENDS FOR CANADIAN NATURAL RESOURCE CAPITAL

Charts 1 and 2 illustrate trends in output from some natural resource industries and natural resource reserves — a measure of natural capital for timber, oil, natural gas and coal over the past 40 years.[5] Three patterns are apparent. The stocks of natural capital are either falling (timber and oil), in an inverted U-shape (gas) or rising in a nonlinear fashion (coal) (where the rate of increase has slowed in recent years). In all cases, however, production has been rising over time. Thus, the declining stocks of timber and oil do not appear to be

CHART 1

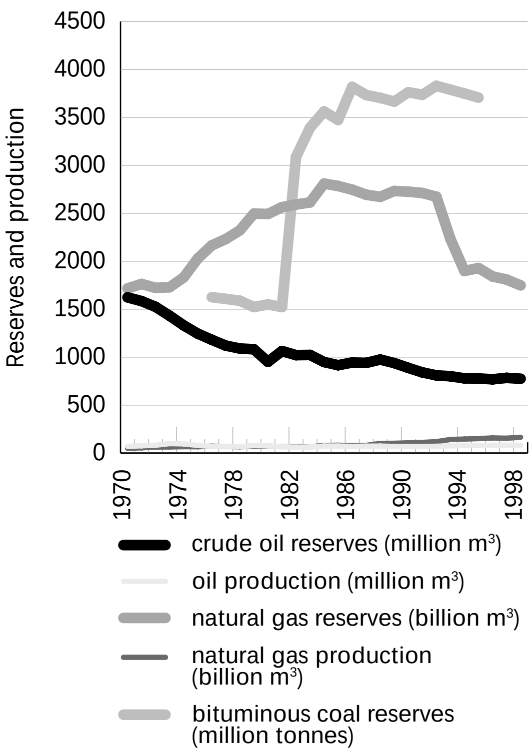
Timber Harvests and Assets, 1961-1997



Source: Statistics Canada. Canada Timber Assets (Volume), Opening Stock, Table Number: 1530030. Timber Harvests, Table Number I530030.

CHART 2

Canadian Energy Reserves and Production, 1970-1998



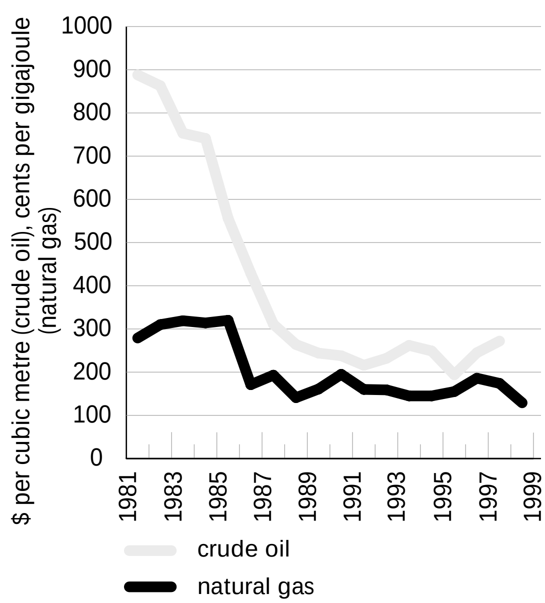
Source: Natural Resources Canada, *Energy in Canada 2000*. www.nrcan.gc.ca/es/ener2000.

restraining current production. Chart 2 indicates why this is so: some natural resource reserves (forests, coal and bituminous coal) are still many orders of magnitude larger than annual production.[6] Canada imports as well as exports all of these natural resources.

Measurement of natural resource reserves is sensitive to current prices in that it includes stocks that are economically recoverable — that is, extractable at the prevailing prices. Many natural resources have been generally falling in real prices over the past 20 years.[7] Long-run real prices of oil and gas trended downward from 1981 to 1998, as shown in Chart 3. Chart 4 illustrates that the real price of timber harvests, while cyclical, generally declined over the period 1961–98. These data suggest that while conventional oil, gas and timber stocks have fallen over time due to extraction/harvesting in excess of new discoveries or regrowth, stocks are still high relative to annual production.[8] If markets are functioning perfectly, none of the resources examined are becoming scarcer in an economic sense, because their prices over the long term have not been rising.[9] This does not mean that declining reserves will not ultimately lead to rising prices: prices depend not only on Canadian supply but also on world supply and, of course, the total demand for the resources. Canadian depletion of many natural resources may simply be too insignificant to affect world prices. This is where the distinction between weak and strong sustainability is important. If specific types of natural capital have substitutes

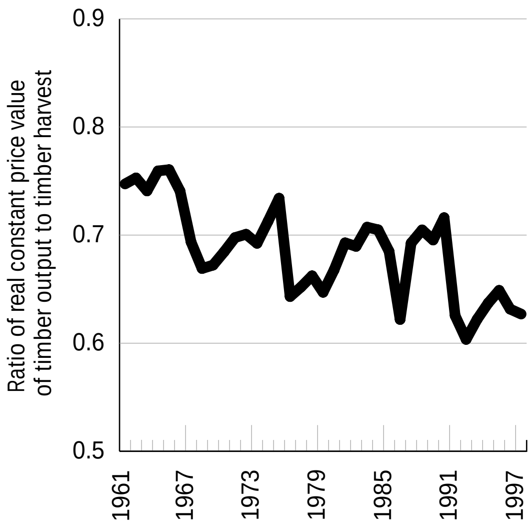
CHART 3

Constant Dollar Prices of Crude Oil and Natural Gas Exports, 1981-1998 (1997 = 100)



Source: Natural Resources Canada, *Energy in Canada 2000*. www.nrcan.gc.ca/es/ener2000.

CHART 4
Real Price of Timber, 1961-1998
(base year 1992)



Source: Computed from Statistics Canada, Timber Harvests and Indexes of Real GDP in Logging and Forestry, Table Number: I607603.

(the same type of natural capital from other sources, labour or reproduced capital), a decline in their stocks will not signal economic dislocation.[10]

Declining natural resource prices may also be the result of other factors. The composition of Canadian output may be changing over time. Technological changes and innovations and rising labour productivity (e.g., due to increases in human capital) can reduce the amount of natural capital required per unit output. That is, the economy may substitute for production that is natural resource-intensive, becoming less dependent on natural capital over time, in which case productivity will fall in the natural resource sectors as those industries decline. However, declining stocks of renewable resources can affect environmental capital such as biodiversity and ecosystem integrity, not to mention quality of life. Substitution may also take place in environmental capital. For example, the use of pollution abatement and control technologies and recycling means that there is less use of the absorptive capacity of the natural environment (and, presumably, less stress on ecosystems). But there are limits to the amount of substitution that is possible with environmental capital. The challenge lies in defining these limits. Environmental resources are addressed again at the end of the paper.

One can get a rough picture of the relative contribution of natural resource capital to total output in the economy by examining changes in real output over time. Table 1 shows that output has risen for all resource sectors except (in 1980-97) fishing and trapping. Real GDP growth for all Canadian industries rose at an average annual rate of 6.5 percent from 1961 to 1980 and 2.6 percent from 1980 to 1997. In the latter period, only one resource industry, coal, exceeded the growth in real output of the aggregate economy.[11] The other sectors grew more slowly. The fishing and trapping industry is a special case; all the data and information available about fish stocks point to a significant decline in natural capital — major reductions in stocks due to harvesting and natural conditions.[12]

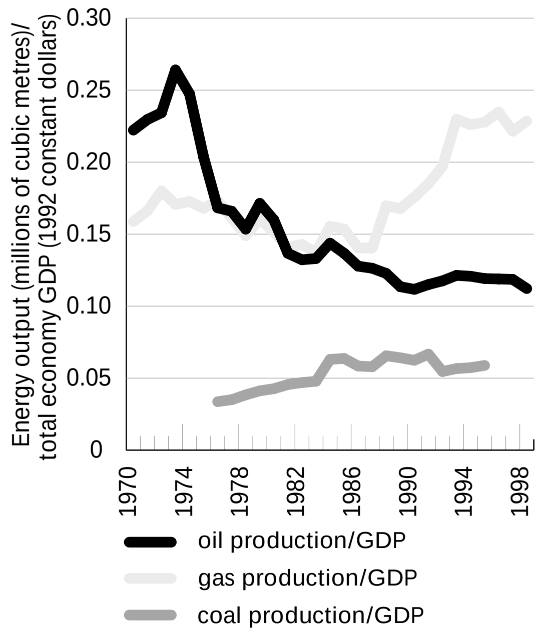
TABLE 1
Average Annual Percentage Change in Real Output for Natural Resource Industries

	% Change in Real Output	
	1961–1980	1980–1997
Agriculture	1.2	2.5
Fishing & Trapping	0.4	-0.9
Logging & Forestry	1.7	0.8
Mining	1.3	1.5
Coal	1.8	4.6
Oil & Natural Gas	2.4	2.5

Source: Statistics Canada, Indexes of Real Gross Domestic Product by Industry, 1992 = 100, Table Numbers: I607601,I607602,I607603, I607704,I607810,I607705.

Declining growth in most natural resource sectors implies that these sectors represent a smaller share of the value of total output over time. This is explained at least in part by the declining real prices of many resources. But one might also infer that there has been a reduction in the essentialness of natural capital in these sectors; put another way, the economy may be developing substitutes for some of its domestic natural capital. This view is supported by data on aggregate energy consumption in Canada over the past four decades. While energy consumption has risen in aggregate and per capita terms (by over 200 percent and 93 percent, respectively, from 1961 to 1997), energy consumed (in physical terms) per unit GDP has fallen by 12 percent (see Environment Canada). However, when one looks at specific energy products and examines total production relative to GDP, a somewhat different picture emerges. Recall from Chart 3 that the real prices of oil and gas fell between 1981 and 1997. The relative importance of energy may thus be even greater than suggested by the energy consumption-to-GDP ratio. Chart 5 shows the ratios to GDP (in constant 1992 dollars) of energy output in physical units for oil, gas and coal. The share of output for coal is rising; natural gas is U-shaped, rising since the late 1980s; and oil is falling. These trends may have implications for sustainability, especially when one considers environmental capital. Production of energy from fossil fuels generates pollution that can damage ecosystems and health.

CHART 5
Physical Energy Output-to-GDP Ratios, 1970-1998



Source: Natural Resources Canada, *Energy in Canada 2000*. www.nrcan.gc.ca/es/ener2000, Statistics Canada, Gross Domestic Product at Factor Cost.

As noted above, all the data presented in this paper are aggregated to the national level. Resource stocks and the importance of natural resources in provincial GDP vary across the country — for example, British Columbia and Alberta are much more resource-intensive than Ontario and Quebec. As well, changes in resource stocks may differ across the country — for example, timber reserves may be falling more quickly in British Columbia than in Quebec. Because of this variability, should one examine natural capital and sustainability at the national or regional levels? This paper focuses on the national level because natural resource capital from one part of the country can be substituted for that in another.[13] It may be argued that even the national level is too limited because natural resources from other countries can be substituted for declining natural capital stocks in Canada. This argument does not hold for environmental resources — one cannot substitute air quality in Regina for that in Toronto.

NATURAL CAPITAL AND PRODUCTIVITY GROWTH

Productivity growth may be linked to sustainability because it indicates scope for improvements in a country's living standards that are, in principle, sustainable through technological advances.[14] For example, technological advances in natural resource production can allow for more output from a given stock of the resource, or offset the natural decline in output or quality of the stock of the extracted resource as its reserves are depleted. Technological advances in oil extraction, for instance, allow for the recovery of more oil from a given pool than was possible 25 years ago; a tree now yields more useable fibre because of advances in harvesting and milling technology.[15] This gets at the heart of what constitutes recoverable reserves of a natural resource. Technology, along with prices and production costs, determines what is economic to recover. On the other hand, if depletion of a natural resource leads to increases in the marginal cost of extraction/harvesting, then, *ceteris paribus*, productivity ought to decline unless there are offsetting technological changes. For example, the marginal cost of pumping oil from a well rises as the oil in the pool is depleted because of a decline in the natural pressure. More capital and labour must be used to extract a given quantity of oil. The sustainability of a natural resource may therefore be connected to productivity. This is not to suggest that one need look only at productivity, because clearly there are many possible indicators of sustainability; the point is that productivity might be one of those indicators. The same concept could apply to environmental capital; however, we know so little about the relationships among environmental capital, productivity and sustainability that it is very difficult to make inferences. One would expect far less substitutability of manufactured and human capital for environmental capital than for natural resources. This is clearly a major research topic in itself.

Two measures of productivity growth are commonly used to gauge the ability of the economy to produce goods and services over time: labour productivity and multifactor or total-factor productivity (MFP or TFP). Labour productivity indicates how much is produced per worker and hence the real income available to the population. In this sense, it links well with sustainability, by showing how much sustainable consumption is possible. Multifactor productivity is used as a measure of technological change. It is the growth rate of output minus the growth rate of the inputs weighted by their input shares, where, generally, only two inputs are included — capital and labour. The "unexplained" portion of output growth is generally interpreted as technological change. It would more appropriately be interpreted as disembodied technological change (or a measure of our ignorance) because, as a residual, MFP is telling us what is not explained by the growth rates in measured inputs.[16] But natural capital is also an input into the production of goods and services and is not captured in most estimates of MFP, so MFP should be adjusted to reflect changes in natural capital. However, even if we could measure natural capital, we could not determine its input share without estimating production (or cost) functions; it is thus part of the residual. The contribution of natural capital to productivity growth has been estimated for individual industries (see Squires 1992; Repetto et al. 1996; Swinand 1999; Harchaoui and Lasserre 2001; Harchaoui et al. 2001; these papers will be discussed in more detail below).[17] Labour productivity and MFP for Canada's natural resource sectors are examined below.

Labour Productivity in Natural Resource Industries

Labour-productivity growth rates for the total economy versus the primary sectors in Canada and the United States are shown in Table 2, for several periods starting in 1989.[18] One can draw several conclusions from this table. Productivity growth in the primary sector as a whole significantly exceeds that in the total economy. While the growth rate for the primary sector dipped slightly in the late 1990s, it then rose almost to the 1989-95 level and remains more than twice as high as that for the total economy. In addition, while the United States has higher productivity growth overall than Canada, the productivity growth of the primary sector in Canada is about twice that of the United States. The positive productivity growth indicates that, over time, the economy becomes more efficient in turning inputs into outputs. If one combines productivity data with measurement of changes in natural resource stocks, it might be possible to draw some inferences about weak sustainability. If, for example, natural resource stocks are declining but labour productivity is rising, the suggestion is that other factor inputs are being substituted for natural resource capital. We cannot say if this process will continue, of course, and one would also want to examine other indicators of sustainability. As well, these inferences are based on aggregate data that obscure many different patterns amongst the primary industries.

Table 3 breaks down the primary sector in Canada into separate industries and

TABLE 2

Labour-Productivity Growth — Primary Sector Relative to the Total Economy, Canada and the United States

	Total Economy (%)		Primary Sector (%)	
	Canada	United States	Canada	United States
1989–1995	1.0	1.2	3.1	1.5
1995–2000	1.6	2.4	2.5	1.1
1989–2000	1.2	1.7	2.9	1.3

Note: Real GDP per worker, average annual percentage rate of change.
Source: Rao and Tang (2001, Table 2).

TABLE 3

Average Annual Labour-Productivity Growth Rates in Resource Industries , Canada

	1961–1973	1973–1981	1981–1989	1989–1997	1989–2000
Agriculture	2.2	2.1	1.3	2.6	5.5
Fishing & trapping	3.3	-0.7	-3.7	-0.6	-0.9
Forestry	2.2	1.3	3.0	-0.8	-0.8
Mining	2.4	-1.5	4.1	1.0	n/a
Coal	5.2	0.8	6.5	5.3	n/a
Oil & gas	1.4	-14.7	- 0.4	3.8	n/a

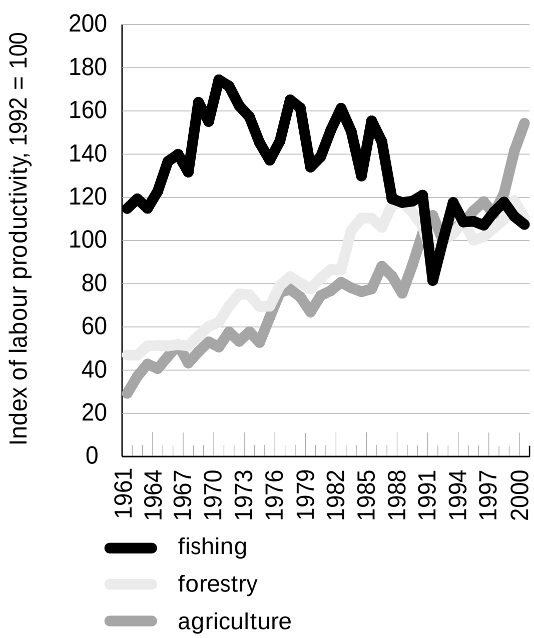
Note: Average growth rates are calculated from peak to peak to be cyclically neutral. Data are not available for mining, coal, and oil and gas beyond 1997.
Source: Statistics Canada, Indexes of Real GDP per Hour Worked, 1961–1997, 1961–2000, Table Numbers: I610101, I610102, I610103, I610204, I610310, I610205.

provides average annual rates of growth in labour productivity over the four decades starting in 1961. The chosen time periods are cyclically neutral — that is, they go from peak to peak in the business cycle. There is no clear pattern. While most resource industries show a slowdown in growth beginning in the 1970s (and for fishing and trapping, consistently negative growth), oil and gas had its highest labour-productivity growth in the 1990s. But even these average rates expressed per decade do not accurately indicate the longer-term trends in each industry.

Charts 6 and 7 show labour productivity for the renewable and non-renewable resource industries over the past 40 years. Chart 6 illustrates the diversity among the renewable resources. Labour productivity has been generally rising for agriculture[19] and forestry, but declining, since the late 1970s, for fishing and trapping. For the entire period, labour productivity in agriculture has grown by 313 percent and forestry by 158 percent, while fishing and trapping has declined by 0.2 percent. Recall from the previous section that over the past 40 years the stock of forest natural capital and most fish stocks have been declining, but labour-productivity trends are quite different for the two sectors. There are many possible explanations for this difference. The role of technological change is examined in the next two sections. The responses of each industry to changing prices may also be a factor. Industries with declining real prices over significant parts of the time series (timber and agriculture) may have restructured and consolidated their enterprises, thus improving labour productivity. But changes in natural

CHART 6

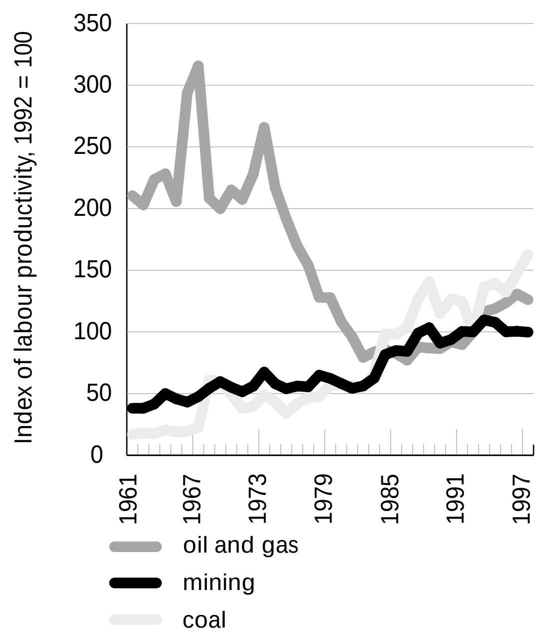
Labour Productivity in Renewable Resource Industries, 1961-2000



Source: Statistics Canada, Indexes of Real GDP per Hour Worked, Table Numbers: I610101, I610102, I610103.

CHART 7

Labour Productivity in Non-Renewable Resource Industries, 1961-1997



Source: Statistics Canada, Indexes of Real GDP per Hour Worked, Table Numbers: I610204, I610310, I610205.

capital may also play a role. Natural capital in fisheries may have crossed a threshold below which sustainable production in the sector is not possible, despite an attempt to substitute other inputs for the declining stock of natural capital. Falling labour productivity is consistent with this argument. Theoretical models of open access and imperfectly regulated fisheries have predicted for many years that harvests exceeding the sustainable yield from the fishery will ultimately exhaust the fishery. Natural capital is clearly essential for this industry. One cannot substitute labour and capital indefinitely to sustain the harvest.

The decline in forest stocks reflects the harvesting of old-growth timber and its replacement with lower-yielding second growth. While the total stock has declined, labour productivity has not been adversely affected because annual harvests represent only a small percentage of the total stock. Annual harvests have risen from 0.6 to 1.4 percent of the timber stock.[20] While this suggests a relatively high "reserves-to-harvest" ratio, timber stocks are vulnerable to losses from natural phenomena such as fire, insect pests, disease, pollution and weather. For agriculture, data are available for measures of natural capital for 1981 and 1996. Total area in farms and land in crops has risen by 3.3 and 12.8 percent, respectively, while that in pasture and summerfallow has fallen by 1.3 and 35.5 percent. These data suggest no clear picture with regard to the impact of changes in agricultural capital on labour productivity in the sector.[21]

Chart 7 illustrates labour productivity for non-renewable resource industries in the period 1961-97. For coal and mining, labour productivity generally rose throughout the period, while for oil and natural gas the picture is more complex, with productivity declining from the mid-1970s to the early 1980s and rising thereafter at a rate roughly comparable to that for mining (until the most recent years).[22] During the 1970s and early 1980s, exploration for new reserves was driven by increases in the real price of energy and was also affected by an export licensing requirement of a minimum reserves-to-extraction ratio. The more extensive and intensive drilling led to large increases in labour (and capital) but little in the way of incremental output. Recall from Chart 2 that reserves of oil were falling. This decline in natural capital would also help explain the drop in labour productivity. Declining stocks of natural capital may have played a role for oil, but not for natural gas. Gas reserves were rising over this period. The data for the mid-1980s indicate that once the reserve-ratio regulation was lifted, exploration activity was based on expected profits, falling when energy prices decreased. Labour productivity has been rising since the mid-1980s. Technological change is now playing a greater role (as will be discussed below). For coal, the reserves of natural capital are enormous relative to current extraction. Mining is an aggregate that obscures developments with individual minerals, and hence it is difficult to explain trends in labour productivity. Reserves (and prices) have declined for some minerals but not for all. In aggregate, however, labour productivity is rising. This suggests that these sectors are weakly sustainable. The important point is that labour productivity and, as seen below, MFP might be helpful adjuncts to the strictly physical indicators of sustainability. Productivity measures may provide insight into the degree of substitution of capital and labour for natural capital. The substitution may be stimulated by declining natural capital stocks and/or technological changes affecting the use of different inputs.

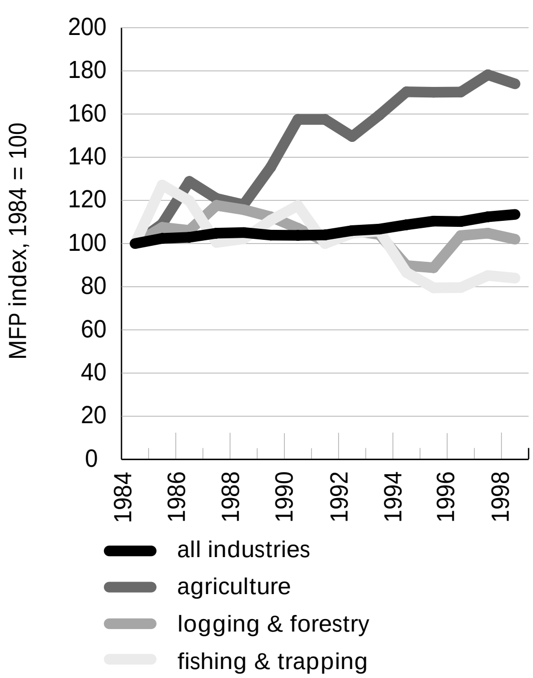
How does labour productivity in the resource industries in Canada compare to that in the United States? Parry (1999) looks at coal, petroleum, logging and copper. His estimates of labour productivity in the United States yield paths over time similar to those in Canada.

Multifactor Productivity in Natural Resource Industries

Charts 8 and 9 present MFP for renewable and non-renewable resource industries compared to that for all industries. As noted above, MFP gives us an estimate of the combined effects of technological change, changes in natural capital over time (if it is an excluded input) and other unexplained factors.[23] As illustrated in Chart 8, of the renewable resource industries, only agriculture shows a generally rising trend, with a rate of growth exceeding that of all industries combined. Forestry and fishing are somewhat more cyclical, but trending downward with rates falling below those of all industries after the early 1990s and with fisheries falling below the rate of the base year (1984). In the non-renewable sectors the trends are quite different, with rates above that of all industries after the early 1990s and rising between 1984 and 1993 — except for coal, which rose throughout the period, with accelerated growth after the early 1990s (see Chart 9).

CHART 8

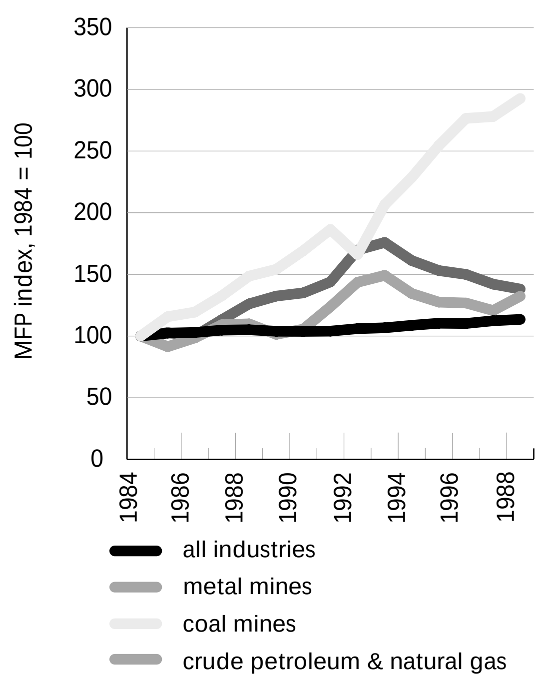
Multifactor Productivity: Renewable Resources vs. All Industries, 1984-1998



Source: Centre for the Study of Living Standards, based on Statistics Canada, *Labour Force Survey*, GDP, and Capital Stock Data, as cited in Natural Resources Canada, *Energy in Canada 2000*. www.nrcan.gc.ca/es/ener2000.

CHART 9

Multifactor Productivity: Non-Renewable Resources vs. All Industries, 1984-1998



Source: Centre for the Study of Living Standards, based on Statistics Canada, *Labour Force Survey*, GDP, and Capital Stock Data, as cited in Natural Resources Canada, *Energy in Canada 2000*. www.nrcan.gc.ca/es/ener2000.

These estimates suggest very different roles of technological change and/or changes in natural capital in the renewable and non-renewable sectors. This subject is explored more fully below for the energy sector and forestry.

While labour-productivity trends in Canada are similar to those in the United States, MFP growth is somewhat different. Table 4 illustrates that Canada's MFP average annual growth was considerably higher than that of the United States over the period 1985 to 1994. Again, one must be careful in selecting a specific period if the trend has been cyclical, but the data for the 10-year period indicate that Canadian resource industries are healthier than their US counterparts. Is this because of greater technological change in Canada than in the United States? That is doubtful. The two economies are closely linked and one would expect technological change to readily flow between the countries. Because natural capital is omitted from the MFP calculation, an alternative explanation might be that declining natural capital had a greater impact on these sectors in the United States than in Canada. An examination of such a possibility is beyond the scope of this paper, but such an investigation is warranted.

It is generally expected that the growth rate of MFP will be lower than that of labour productivity, because the growth rate of the capital stock (or capital plus intermediate inputs) is typically higher than that of employment — that is, capital-labour ratios tend to rise over time. If we look at average annual growth rates in the two measures of productivity for Canadian resource industries, we find that they are highly variable year to year and that in a number of years MFP exceeds labour productivity. This variability suggests that omitting natural capital as an input in MFP measurement skews the estimates in an unexpected direction. This skewness may arise because the MFP estimates do not distinguish between impacts of changes in natural capital and those resulting from technological change. If natural capital is rising over time, traditional MFP estimates will overstate technological change and vice versa for a given level of output growth. Traditional MFP that is still rising while natural capital is declining might be an indication of weak sustainability, because technological change and substitution of other inputs may be occurring. When MFP declines consistently over time, concern about sustainability is warranted.

The relationship between MFP and labour productivity is exemplified by the fishing industry. A study of several fisheries in the United States shows that omitting natural capital from productivity measurement does bias the estimates. Squires (1992) measures total-factor productivity (TFP) in the open-access Pacific coast trawl fishery, explicitly accounting for changes in the abundance of fish stocks. TFP properly measured is "the residual after allocating the growth rate of output among changes in variable inputs, capital, and resource abundance" (Squires 1992, p. 225). Squires compares the conventional measure of TFP with the measure inclusive of natural capital. He finds that in years when

TABLE 4

Average Annual Growth in Multifactor Productivity (Percentage), 1985–1994

	Coal	Petroleum[1]	Logging
Canada	11.3	5.8	-1.8
United States	1.4	3.7	-2.1

[1] Includes natural gas in Canada.
Source: Parry (1999, Figure 5), Centre for the Study of Living Standards as cited in Natural Resources Canada, *Energy in Canada 2000*. www.nrcan.gc.ca/ es/ener2000.

fish biomass is declining, conventional TFP understates "true" TFP, which includes the resource stock, and that, analogously, in years when biomass is rising, conventional TFP overstates productivity growth adjusted for changes in natural capital. This is because in abundant years it is easier and hence cheaper to harvest fish, and excluding the resource stock makes it look as though technological change, not the increase in the resource stock, is the contributing factor to the increased outputs. In Squires's time series, productivity growth is on average about half that of measured TFP. Changes in the resource stock (and other variables such as capacity utilization and the catchability of the fish stock) are responsible for a significant portion of the measured productivity growth. Proper accounting for changes in natural capital (both quantity and quality) can thus be extremely important in providing an accurate picture of productivity growth and sustainability.

LINKS BETWEEN NATURAL CAPITAL, TECHNOLOGICAL CHANGE AND SUSTAINABILITY OF NATURAL RESOURCES

Multifactor productivity growth captures changes in natural capital and in technology and other unexplained factors, and, as we saw above, it is important to estimate natural capital inputs in order to accurately measure productivity growth. But natural capital and technological changes are not mutually independent. For example, depletion or degradation of natural capital may stimulate investment in research and development to increase the stock size. For non-renewable resources, improved exploration techniques may result in more discoveries of viable reserves. With renewable resources, genetic and selective breeding techniques may increase biomass (e.g., timber volume, fish weight and size, crop yields). New extraction or harvesting technologies may yield higher recovery of a given stock of total reserves. There are many examples: offsetting the natural decline in pressure for oil and gas deposits; finding more fish in the oceans due to satellite mapping of stocks; or recovering more usable timber from a given tree due to advances in harvesting and sawmilling technology.

A second factor may be regulation. This is particularly relevant for environmental resources. Government policies that require producers and consumers to reduce waste emissions may induce technological changes that reduce the amount of emissions per unit output, thus sustaining the stock of environmental capital. For example, less polluting inputs could be substituted for those that release high levels of waste, or technologies could be introduced that turn waste products into inputs that can be used on-site or by other businesses. Regulation also plays a role in natural resources. For example, regulation of open-access fisheries may induce firms to manage aquatic stocks in a more sustainable manner.

Innovation takes time, with regard to both the discovery of appropriate technologies and the diffusion of those technologies into a particular sector from other sectors or other countries. The innovations we see today may be the result of changes in natural capital that occurred some time ago, or that occurred elsewhere and have spilled over into Canada. Thresholds may have to be crossed wherein the decline in natural capital (relative to production and consumption) reaches a point where it pays to look for ways to augment the stock or recover more of the extracted resource per unit of stock. The precise relationships are difficult to determine. Several examples of technological change in natural resource industries might serve to illustrate some of the factors responsible.

Examples of Technological Change in Natural Resource Industries

The papers published in Simpson (1999) examine technological changes and innovations in four US natural resource industries: coal, petroleum, copper and forestry. Although the lessons learned are applicable to the Canadian counterparts, examples from the energy sector and forestry show that the technology transfer from the United States to Canada is incomplete. A snapshot of each industry may help to "explain" changes in productivity in these industries over the past 40 years and highlight the roles played by depletion of the natural capital and environmental regulation.

Coal. Coal is an "old" natural resource. It has been used as an energy source for hundreds of years and is also used in the manufacture of steel. Coal is a significant input into electricity generation in the United States, less so in Canada. As shown in Chart 2, Canada has enormous reserves of coal (this is also the case worldwide); there is no fear of depletion for the foreseeable future due to exhaustion of the natural capital stock.[24] Natural capital stocks are thus not a constraint on coal production. Labour productivity and MFP growth rates for coal have been very high in some time periods — among the highest of all the natural resources (as illustrated in Tables 3 and 4 and Charts 7 and 9). Labour-productivity growth averaged 4.1 percent in the United States over the period 1950 to 1995, compared to 3.1 percent in Canada over the period 1961 to 1995.[25] Thus, technological changes in the United States have likely spilled over into Canada. The industry has seen a large decrease in labour intensity due to the adoption of new technologies.[26] For example, ever larger and more sophisticated equipment (e.g., large electrified draglines) have been deployed to extract ore in surface mining, while longwalling techniques have improved productivity in underground mines. The industry is pervaded with the use of remote-control computer processes and other information technology innovations. The capital intensity of the industry has increased considerably over the past 40 years, but MFP has also increased, suggesting continued and strong technological change. Recall, however, that if coal reserves are growing, MFP measures may be overstating technological change.

Innovation has also been stimulated by environmental and health and safety regulations introduced in the 1970s. For example, the US *Clean Air Act* legislated reductions in sulphur emissions from fossil fuel combustion in electric power plants, resulting in the development of new technologies to reduce sulphur. Labour productivity in the US coal industry fell by 1.9 percent during the 1970s. The regulations, along with periods of labour unrest and the entry of inefficient producers responding to high energy prices in the 1970s, were deemed responsible. But over the period 1980 to 1995 labour productivity grew at an average annual rate of 6.6 percent, a growth rate significantly above that of the pre-regulatory period (e.g., 4 percent between 1960 and 1969). Improvements in labour relations, falling coal prices, and increases in efficiency and new marketable by-products (sulphur and methane) recovered from pollution-abatement technologies are the reasons offered for the boost in productivity. In Canada, concerns over local and regional air pollution led to guidelines and regulations to reduce sulphur emissions from fossil fuel combustion and the adoption of the new pollution-abatement technologies by coal users (e.g., electric utilities in Alberta and Saskatchewan). Coal is thus an example where regulation-induced technological change has been a major factor in productivity growth, once the adjustment to capital acquisition and new technologies occurred.

Petroleum. In contrast to coal, with its vast stocks of natural capital, oil and gas reserves have been declining. Canadian conventional oil reserves in 1998 were approximately half of what they had been in 1970 (see Chart 2). In this sector incentives for the development of new technologies are therefore more likely to be based on the depletion and degradation of reserves. Innovations that support the discovery of new reserves of oil and gas, or greater recovery from existing reserves, help to keep extraction costs from rising as quickly as the stocks of reserves are drawn down. Recall as well that the real prices of petroleum resources fell over much of the period, intensifying the need to reduce costs to keep the North American industry viable. Given the fact that supply and demand are governed by a world price, North American producers compete with lower-cost suppliers such as those in the Middle East. Bohi (1999) identifies three innovations that have lowered the costs of exploration and development of deposits: three-dimensional seismology, horizontal drilling and deepwater drilling. Other innovations have improved the process of recovering oil from existing wells; for example, replacement of losses in natural pressure can increase the total reserves extracted from a given deposit. Oil production from oil sands and other "unconventional" sources represent technological advances that have significantly lowered the costs of extraction and processing.[27] Environmental regulations, while inducing some technological change, are believed to be a less significant factor for petroleum than for coal (Simpson 1999).

Chart 7 shows a fall in Canadian labour productivity for the oil and gas industry between the mid-1970s and the mid-1980s. The United States also experienced this drop, even though it did not have the same regulatory environment, the reason being, according to Bohi, that the number of wells drilled was greatly reduced during the period — by the 1990s, drilling in the United States was half that seen prior to 1973 — with no corresponding reduction in labour inputs. In Canada, oil and gas exploration declined by 60 percent over the period 1983 to 1995. Helliwell et al. (1989) argue that the decline in the 1980s would have been even greater had the National Energy Plan not been introduced. Private R&D expenditures (in constant dollars) were essentially flat from the 1980s to the late 1990s but may now be increasing again (United States Department of Energy 2000). Government investment in energy R&D declined by 75 percent between 1984 and 2000. Over the same period electric-utility R&D increased steadily (2 percent per year), with a portion devoted to renewable energy resources. Canada is also a world leader in fuel-cell technology. Average annual productivity growth, after falling in the 1970s and 1980s, increased significantly in the 1990s. Canada also imports R&D, so the decline in domestic R&D may not be correlated with decreasing domestic innovation over time. Given the cyclicity in this sector, it is difficult to draw a general conclusion.

Copper. Copper mining is almost as old as human civilization. The industry in North America dates back to the 19th century. Although some discoveries have been made in the past 40 years, reserves in Canada and the United States were generally depleted by the 1970s to the point where the industry could no longer compete with lower-cost mines in other parts of the world. Copper prices remained low due to sufficient worldwide supplies and substitution away from copper inputs (e.g., fibre optic cable substituting for copper wire). In mining, extraction costs are affected by both the quantity and the quality of natural capital. The "best" ore bodies are typically extracted first. As depletion occurs, labour (and MFP) productivity decline, because poorer-quality deposits either reduce output per unit input or require more inputs per unit output. The situation facing US and Canadian producers was to either find innovative ways of recovering copper at costs that would allow for continued production, or shut down. There was essentially no productivity growth in the US copper industry from 1960 to 1975.[28]

In this industry major innovations did occur in response to depletion, degradation and lack of productivity growth. A notable example is the recovery of copper from mine tailings using a chemical process that required the development of new solvents.[29] Wastes are literally "re-mined" to extract copper not recovered using older, less efficient technologies, essentially allowing a higher percentage of metal to be ultimately recovered from an orebody. The process has cut the tonnes of waste per tonne of ore mined by over 35 percent; in 1995 output was 21 percent above 1970 levels and 72 percent above 1985 levels. Labour-productivity growth reflects this technological boost, increasing by 50 percent between 1980 and 1986.[30] Re-mining has a limited life, however, and these deposits will be exhausted. By the 1990s, productivity growth, while still much higher than it had been in the 1960s and 1970s, had begun to flatten. Copper illustrates how technological change can extend the life of a non-renewable natural resource. Copper is not an essential resource for most of its uses. Unless further technological change occurs, therefore, productivity in this industry is expected to fall in the United States as the industry declines.

Forestry. Forests are a renewable resource, but, as in the case of the non-renewable commodities discussed above, their natural capital can be depleted, because old-growth forests often have far more wood volume per hectare than the secondary forests that replace them (whether these are the result of planting or natural regeneration). In the case of forestry, soil fertility is the depletable resource. Unless forestry companies invest in inputs to improve fertility, the productivity of the land will decline. Another factor is insufficient reforestation. This can occur when property rights to forest land are insecure: harvesters have no guarantee of being able to harvest, 30 to 80 years hence, a tree they plant today. The problem is clearly exacerbated by long growing periods for this "crop." Property rights may be insecure, even in North America, because of inconsistent government policy — for example, with regard to leasehold arrangements or bidding policies for harvesting rights on Crown lands. In the 19th and early 20th century, many forests were essentially open access, allowing harvesters to "cut and run." The industry can now be characterized as having depleted much of its high-quality timber. Most of the industry is harvesting secondary growth, and for the segment of the industry that is still cutting old growth the sites are increasingly inaccessible. As shown in Chart 1, over the past 40 years the stock of timber has steadily declined in Canada. Other factors contributing to the decline in forest natural capital are environmental regulations, land-use restrictions, and conversion of forested lands to other uses such as agriculture, housing and protected sites. This removal of land from timber production represents an interesting tradeoff. The decrease in the supply of timber lands reduces natural capital, which could, in turn, lower productivity due to reduced input and potentially higher prices for the remaining land. On the other hand, greater scarcity of natural capital could stimulate R&D in intensive forestry technologies.

Charts 1, 4, 6 and 8 show that the Canadian forest industry is characterized by steadily declining natural capital (timber stocks), positive labour-productivity growth and, from 1986 to 1994, declining MFP. A closer look at the British Columbia industry reveals factors responsible for productivity changes and the potential for sustainable production (Sedjo 1999). Over the period 1970 to 1981, labour productivity in the BC industry was relatively flat; it rose by over 60 percent between 1981 and 1987, then fell by about 9 percent between 1987 and 1992. In the 1970s unit labour costs rose by 144 percent, reflecting a period of significant labour unrest, but after 1981 growth in labour costs sharply declined, to about 1 percent per year. Despite that earlier growth in labour costs, net logging costs[31] were essentially flat from 1975 to 1993. After the 1970s, total costs were held down through the introduction of labour-saving innovations such as a new means of attaching felled trees to cables to remove them from the site (grappling). Innovations in sawmilling technology — for example, computer-guided systems to recover more usable wood per tree — have been adopted in part of the industry. In the 1990s, the province imposed new policies such as stricter standards for the construction and maintenance of logging roads, ostensibly for reasons of environmental protection. These regulations limit the use of the labour-saving grappling technology, hence increasing logging costs. Other regulations that restrict harvests on sites adjacent to recently cut areas may lead to extensive logging in more remote areas. This will further increase costs and could help explain the negative growth rates in labour productivity in recent years. Estimates of the impact on costs range from $220 million to $1.5 billion annually (see, e.g., van Kooten 1994; Binkley 1995).[32] New innovations do not appear to be emerging in the BC forest industry.[33]

In the United States, labour productivity increased until the mid-1980s, then slowed; average annual MFP growth was negative after the mid-1980s. Unlike Canada, the United States has essentially exhausted its old-growth forests. The decline in productivity could be a result of this loss of high-quality natural capital and its substitution with lower-quality secondary growth, which produces less output per unit input. These factors might be interpreted as reducing the sustainability of timber resources. However, the United States, helped by favourable geography and climatic conditions, has been moving towards a more intensive forestry practice: plantation forests. Timber production is being stepped up through innovations such as biotechnology and genetic selection for high-yield species, more intensive use of fertilizers and pesticides, and forest practices such as optimal thinning and irrigation. However, intensive forest management has environmental implications: monoculture and increased use of fertilizers and pesticides may adversely affect other industries and wildlife and may reduce biodiversity.

These four industries illustrate the diversity of responses to changing levels of natural capital and the impact of regulation. There is ample evidence of new technologies being adopted to mitigate or offset declining stocks of natural capital. What are the implications for sustainability? Two questions arise. First, are technological change and innovation necessary to ensure productivity growth in natural resource sectors? The answer appears to be yes for the cases discussed. There are no significant threats to the sustainability of production of these natural resources or the production of goods using them as inputs.[34] But it is clear that technological change has kept production levels from falling and/or costs from rising as much as they might. Second, how well can the past predict the future with regard to technological change and innovation? This brings us back to the issues of identifying which types of natural capital are essential to sustainable production and which sectors of the economy are at greatest risk with regard to dependence on natural capital. This is a topic that requires more research.

UNMEASURED FACTORS IN PRODUCTIVITY GROWTH: ENVIRONMENTAL SERVICES

The discussion has focused to this point on natural capital in the form of natural resources. Environmental resources are another type of natural capital. Unlike most of the examples above, environmental resources are essential to the sustained life of humans and all species. We can sustain consumption and production with a degraded natural environment — for example, lower air quality, a depleted stratospheric ozone layer, less biodiversity, fewer natural areas, and climate change that raises average temperatures and increases variability of weather events such as intense storms, flooding and unseasonable temperatures. There will be tradeoffs in the form of higher insurance and health costs, loss of enjoyment from natural areas, less outdoor recreation, and higher expenditures to mitigate and adapt to the effects of ecosystem degradation. Clearly we will not be sustaining the same quality of natural capital — clean air is replaced by dirty air. If people value clean air, they will view environmental degradation as a loss in their utility due to lower consumption of clean air. This loss in consumption is difficult to measure using market values; one must turn to non-market approaches.[35] Thus one must define the notion of sustainable consumption more carefully when addressing environmental capital. The loss in environmental capital could also show up in productivity measures. As ecosystem natural capital declines and/or the stock of accumulative pollutants builds up, productivity may begin to decline. Productivity measures may, however, lag behind other indicators of sustainability because of time lags or thresholds in people's perception of the impact of environmental degradation on them and on ecosystems.

We lack ecosystem degradation indicators sufficient to determine the impact of environmental natural capital on productivity. This is an area of active research and data collection by governments, NGOs and research institutes worldwide. One problem is that we have no comprehensive measure of environmental capital. There are many indicators — ambient air quality; emissions of specific air, water and land pollutants; amount of protected lands; crude measures of biodiversity; and so on. But what is one to do with these numbers? How can they be linked to productivity and, in turn, to the sustainability of consumption? Various organizations have compiled sustainability indices from the indicators of environmental capital (and other variables). The problem is that these are largely "black box" exercises that impose weights on each indicator to perform the aggregation. In principle, these weights should be the proportionate contribution of each indicator to the outcome variable (e.g., sustained production, quality of life). But in the absence of any sort of "production function" showing how the various environmental inputs are combined to produce output, the weights become arbitrary and, often, subjective. This does not mean that these exercises are without value. They are a start, and if construction of the index is transparent and consistently measured over time, they can help draw a picture of the role of environmental capital in sustaining economies.[36]

A more modest approach is to examine the contribution of environmental natural capital to productivity growth in the context of specific industries. The effect of leaving environmental capital out of estimates of productivity is analogous to that of leaving out natural resource capital. As environmental capital is used up, its price will rise if markets reflect the scarcity of environmental goods or if greater public awareness of the benefits of environmental goods leads to pressure for more regulation. If the price goes up and environmental capital is not included as an input, measured productivity growth will understate the extent of real productivity growth, with the divergence a function of the amount of environmental capital as a proportion of total inputs. If environmental capital is an insignificant input, measured productivity will approximate actual productivity.

Several studies have tried to estimate the difference in MFP with and without environmental capital. Repetto et al. (1996) calculated MFP with and without environmental capital for US industries expected to use varying degrees of environmental capital. They impute a value to emissions of an industry based on estimates of damage from pollution. If pollution levels fall, the net value of output rises more rapidly than when pollution levels are not incorporated. As Kolstad (2000) notes, this is not quite the same as changing the price of the environment over time but is conceptually similar. Two industries, electricity generation and agriculture, illustrate their results for the period 1970 to 1990. As noted above, the US government introduced air-pollution regulations in the 1970s. This increased the cost to electrical utilities of using the natural environment but had little effect on agriculture. The traditional measure of MFP shows a decline in productivity growth of about 9 percent over the period. If environment is included as an input, however, productivity growth is around 12 percent over the period, relative to a base year of 1970. The divergence in MFP with and without environmental services is negligible for agriculture.

Conrad and Morrison (1989) also look at the impact of environmental regulation on productivity growth. They assume that pollution regulations are socially efficient in that they correctly balance the marginal damage caused by pollution with the marginal costs of abatement. This is unlikely to be the case in practice. They also assume that pollution abatement is entirely a capital expenditure. This is also not the case, but it is not a bad proxy for many manufacturing industries (their data set). Looking at the United States, Canada and West Germany, they find that for a period when environmental regulations were minimal (1960-67), traditional productivity growth measures were approximately the same as an estimate of productivity inclusive of environmental inputs; but for a period during which many environmental regulations were introduced (1972-80), the traditional measure understated the environment-adjusted measure (annual average rates of 2.2 and 2.4 percent, respectively). The effects were less pronounced for Canada (a divergence of 0.06) and West Germany (a divergence of 0.14) than for the United States. During the period 1972 to 1980, Canada's environmental regulation was on average much less stringent that that of the United States. These results suggest that measured productivity growth is understated in periods when environmental regulations are tightening, to reflect growing scarcity of environmental quality.

Swinand (1999) calls MFP adjusted for changes in the level of pollution "total resource productivity" (TRP).[37] Estimating production functions for different regions of the United States, he calculates MFP and TRP for agriculture, using pesticide pollution as his environmental variable. His results corroborate those of Repetto et al. regarding the small impact of environmental regulation on agriculture. He finds that when growth in pollution levels exceeded growth in output, TRP was less than MFP and vice versa. For example, over the period 1989 to 1993 agricultural output was growing at an annual rate of 1.1 percent, pollution was falling by 29.5 percent and TRP exceeded MFP by 0.15 percent per year (1.36 versus 1.21 percent). His results illustrate the level of complexity needed to properly establish the relationship between MFP and TRP. Doing this at the level of the aggregate economy is a daunting task.

Harchaoui and Lasserre (2001) estimate the difference between MFP and TRP when emissions of greenhouse gases are included as an input into the production processes of the Canadian business sector.[38] Modelling the production structure (cost functions) of 37 industries over the period 1981 to 1996, they find that the private shadow value of reducing greenhouse gas emissions is significant for a number of industries. Once the value of greenhouse gas emissions as an input into production is included in productivity estimates, they find that for these industries TRP grows on average by half a percentage point a year faster than conventional MFP. The difference is that costs associated with emission reductions are interpreted as productivity losses in conventional TFP. TRP grows faster than MFP because a number of industries have reduced their greenhouse gas emissions (due to public pressure, anticipated regulation or other reasons). This represents an additional efficiency gain over that measured by conventional MFP.

Chart 10 presents a very crude estimate of the relationship between GDP and pollution for Canada, showing the ratio of GDP to ambient concentrations of the five air pollutants responsible for deterioration of urban and regional air quality. While the slopes of the curves vary considerably, the ratio is rising except for ground-level ozone (O_3).[39] Over the period 1979 to 1996 output growth does not appear to be at the expense of lower levels of aggregate air quality.[40] Thus, one would expect TRP for the aggregate economy to be above MFP if the environment as an input were explicitly taken into account. These numbers are only suggestive of a trend. Air pollutants are one indicator of environmental quality. Other indicators suggest a deterioration of environmental capital (e.g., declining water quality in some regions of the country, loss of ecosystems). The work on measuring MFP inclusive of natural capital is just beginning.

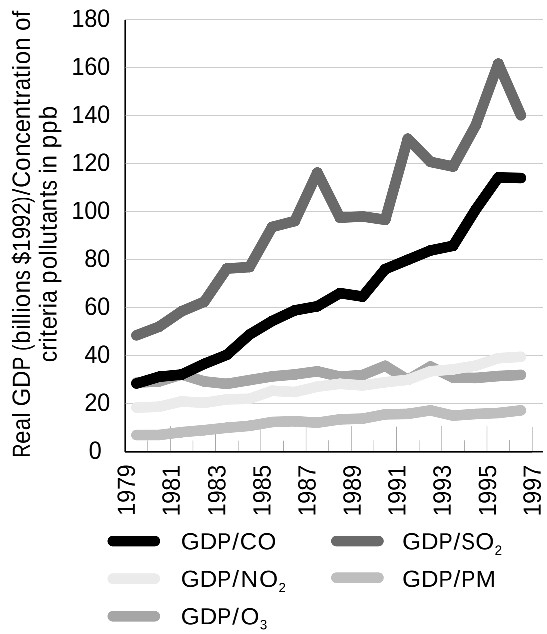
Do Productivity Estimates Help Predict Sustainable Economies?

This paper has examined productivity in Canadian natural resource industries in some detail in order to determine whether depletion of natural resource capital has affected productivity growth. It has also addressed, to a much lesser extent, the relationship between environmental natural capital and productivity growth. Limitations of data and lack of published studies preclude in-depth examination of all components of natural capital. Do any conclusions regarding sustainability follow from this discussion? Is Canada on a path of continued production and consumption, without the destruction of our natural environment? This we do not know. The good news and bad news can be summarized as follows.

On the positive side, it appears that for the non-renewable resource industries examined, changes in the stock of natural capital have not led to a sustained decrease in labour productivity or MFP. Technological change, whether induced by environmental regulation or depletion of the natural capital stock, appears to be contributing to continued productivity growth. Production of these natural resources has been weakly sustainable despite falling levels of natural capital. For the economy as a whole, it has been suggested that the natural resource inputs, with the exception of energy, may represent a smaller input

CHART 10

GDP-to-Pollution Ratios, Criteria Air Pollutants, 1979-1996



Source: Statistics Canada, Gross Domestic Product at Factor Cost. Environment Canada (1999) *State of the Environment, SOE Technical Supplement No. 99-1*, p. 5. *Urban Air Quality, Technical Appendix*, Spring 1999, www.ec.gc.ca/ind/English/Urb_Air/Tech_Sup/uasup5_e.cfm

share in aggregate production now than in the past. This changing composition of output also implies continued sustainability, because labour and human capital, reproduced capital and other materials appear to be substitutes for natural capital. Canada is a small, open economy, and as our stocks of natural capital diminish, inputs from other countries can take their place. This, too, may contribute to sustained productivity growth domestically (but may have adverse effects on the sustainability of foreign economies).

There is, however, a dark side, or at least a high degree of uncertainty about the contribution of natural capital to productivity growth and sustainability. The productivity measures for the renewable industries indicate declining sectors. This is consistent with other evidence of problems in these sectors. The fishing industry and fish stocks in general (and also some sport fisheries) are in trouble. These are predominately open-access resources where regulations have not been effective in ensuring sustainable stocks. Productivity (labour and MFP) has been falling over time. These resources are certainly not essential to continued production and consumption — people can substitute other food for fish — but these industries do affect the viability of many communities. There is also the growth of fish farming, a controversial issue in terms of its environmental impact. What we do not know are how the loss of a number of fish species will affect aquatic ecosystems and whether there will be other negative spillovers for society. Forest stocks are declining and MFP lies below that of the all-industry aggregate. Energy resources are another case in which it is not yet clear whether our path is sustainable. Productivity growth has helped sustain production of fossil fuels in recent years. Stocks of conventional oil and gas are declining, but technological changes may help to keep total oil reserves robust due to oil supplied from oil sands. In any event, there are substitutes for fossil fuels, and if markets are functioning properly and supplies do decline, rising prices for increasingly scarce fuels should accelerate the development of technologies to substitute alternative energy sources such as fuel cells. Fossil fuels are also major sources of pollution, so their use as natural resource inputs also has implications for stocks of environmental capital. This is where our ignorance about the state of our environmental capital and its impact on productivity and sustainability is evident. We do not know if we are passing thresholds (e.g., with climate change) that will lead to very high costs of mitigation or adaptation in the future, reduce productivity and, hence, drive us onto a non-sustainable path. This uncertainty has led many researchers to advocate taking a precautionary path that requires the use of efficient environmental regulation as a complement to economic growth.

Estimating productivity changes for the Canadian economy, ideally adjusted to reflect changes in natural capital, is a worthwhile undertaking. Doing it properly requires more data and analysis at both aggregate and micro levels. Falling productivity in sectors that rely on natural capital suggests that technological change is not keeping up with depletion, that substitute inputs are not readily available and that regulation is not addressing the market failures that are associated with resource use (open access, pollution externalities). Reductions in productivity may be seen as a warning that production and consumption are moving onto a path of non-sustainability.

NOTES

1 Ideally, one would assess the importance of natural capital in the production of all goods and services. This is beyond the scope of this paper primarily because of data limitations, especially for ecosystem or environmental capital (defined below). Natural capital is clearly essential to the production of extracted natural resources. However, human capital, produced capital and technological changes affecting all aspects of natural resource production, from exploration to extraction, also play vital roles. It is the changes in the relative importance of these factor inputs over time that is a focus of the paper.

2 Examples are the so-called KLEM — capital, labour, energy and materials — production and cost functions that were estimated in the 1980s.

3 Some renewable resource stocks, namely fish and other wildlife, are difficult to observe in nature — for example, locating a migratory fish stock in the oceans. Natural capital data for these resources are very slim and are limited to studies of individual species. Aggregate data are not available.

4 Economic analysis of sustainability dates back to classic pieces such as Jevon's concern about using up coal resources in 19th-century England and Malthus's fears about the limits to food production. The 20th-century literature emanates from pieces such as Hotelling's (1931) theoretical model of non-renewable resource production, the open-access renewable resource model (e.g., Gordon 1954), Barnett and Morse's (1963, 1979) work on scarcity and growth, the Club of Rome's limits to growth (Meadows et al. 1972) and much theoretical literature spawned by these works. Economists have certainly been concerned for centuries about the contribution of natural capital to sustainability. But what is sparse is the systematic inclusion of natural capital into economic analyses of productivity growth and, in turn, the linkage of productivity growth to sustainability.

5 Reserves data are the most readily available estimates of natural capital. There are several ways of estimating reserves, each having advantages and disadvantages. The estimates presented in this paper are thus illustrative, not definitive. While coal reserves are shown on Chart 2, production of coal is not, because it would not show up on the scale presented. Estimates of other forms of natural capital — soil depth, arable land, fish stocks — are less readily available and hence not presented here. One can also obtain estimates of the value of the same natural resource stocks presented here. Values fluctuate more than physical stocks due to volatility of prices. Ideally, one would also want to know marginal costs of production, as this would be another indicator of scarcity and hence sustainability. Data on marginal costs are not available at a macro level. One would also like to compute sustainable yields of renewable natural resources. This could be done on a more disaggregated basis — for example, for a specific region or province.

6 Other Canadian reserves are much smaller — for example, oil and natural gas reserves are approximately 20 times current production. On the other hand, ultimate recovery of oil extracted from tar sands is estimated to be approximately 600 billion cubic metres, enough to last many decades at current rates of consumption. See Natural Resources Canada (2000).

7 This is the case for oil and gas, many minerals and timber (although timber is cyclical), but not for many types of fish.

8 For non-renewable resources, exploration and development is dependent on expected profits. Low oil and gas prices in the 1990s discouraged such investment. Recent price increases, combined with reductions in costs due to innovation, have stimulated drilling in recent years. For example, total wells drilled (dry, oil, gas) went from 10,000 in 1998 to approximately 18,000 in 2000, according to the Canadian Association of Petroleum Producers (2002).

9 A better measure of the scarcity of new stocks of a natural resource is the marginal cost of discovering new reserves, in the case of non-renewable resources, or the marginal cost of growing an incremental stock of renewable resources. This sort of data is not readily available for all natural resources and aggregate estimates may obscure significant differences across regions.

10 Substitution can thus come in many forms — for example, the same natural resource from other countries or recovered from more intensive recycling, or petroleum from oil sands rather than conventional sources.

11 For oil and gas and agriculture, the average annual growth rates are slightly below that of the aggregate economy. One should also be cautious about using specific end points for computing average annual growth rates.

12 The cod fishery is an example of how excessive harvesting has depleted the stock to the point where virtually no commercial harvests are viable and the stocks themselves may be irreversibly exhausted. Stocks of several Pacific salmon species also have declined significantly in recent years due to changes in water temperature, migration patterns, harvesting, disease and other factors that are not all clearly understood. Technological change may also be contributing to the depletion of fish stocks. For example, GPS and satellite tracking of fish stocks allows harvesters to accurately track a declining stock, thereby reducing increases in harvesting costs.

13 If one's focus is on sustainability of economic activity in a region — for example, resource-dependent locations — then, clearly, a national focus is inappropriate. This presents a dilemma for sustainability: at what scale should it be measured?

14 See Andrew Sharpe's paper in this volume for a more in-depth discussion of measures of productivity and what they mean for the economy and sustainability. See also Sharpe (2001) and Smith and Simard (2001).

15 More examples are provided later in the paper.

16 See, for example, Lipsey and Carlaw (2000) and Lipsey (2002) for critiques of TFP as a measure of technological change.

17 Note as well that even if natural capital is included in MFP, there may be unobserved factors in addition to technological change included in the residual.

18 All labour productivity figures for Canada represent the entire primary natural resource industry. This means they will include both production and non-production workers as well as those in initial harvesting or extraction plus some processing (e.g.,

sawmilling and pulp production, on-site concentrating of ores). Separating out the primary harvesting/extraction activities on their own would have to be done by province and most likely would involve micro-level studies.

19 One must be cautious with labour productivity measures for agriculture, because wage income is low relative to total income. Labour productivity overstates productivity in this sector. In all these estimates of labour productivity, labour is measured as hours worked.

20 Timber stocks have declined from 14.7 to 12.9 billion cubic metres, while harvests have risen from 92.2 to 181.2 million cubic metres.

21 A detailed examination of agriculture is beyond the scope of this paper. There are a number of estimates of agricultural production functions, and the role of natural capital in agriculture may be better gleaned from this work.

22 It is unfortunate that oil and gas are aggregated in Statistics Canada's series on labour productivity, because, as Chart 2 illustrates, their stocks of natural capital do not always move in the same direction.

23 One important barrier to using the quantity of natural capital as an indicator is that it is both the quantity and quality of natural capital stocks that affects their use. The absolute quantity of natural capital can be constant, but its quality can decline over time due to extraction and degradation. The declining quality may adversely affect productivity and also affect sustainability. For example, fish biomass may be constant over time, but salmon may have declined while bottom-feeders have risen. Salmon is a human food fish, while a number of bottom-feeders may be fit only for cat food and fertilizer. Similarly, forest biomass may be constant over time, but see a shift in age classes or types of timber. One must also be very careful with mineral reserve data, due to changes in quality of deposits.

24 Coal may be "economically depleted" if, due to environmental considerations and the development of less pollution-intensive energy sources, demand diminishes over time. It is possible that demand for coal as an energy input will effectively go to zero long before the stocks are depleted. If so, coal is clearly not an essential natural resource.

25 If Canadian labour productivity data were available back to 1950, Canadian numbers would probably be at least as high as those for the US.

26 Information about coal is taken from Darmstadter (1999). See also Ellerman et al. (2001) for an analysis of productivity in the US coal sector.

27 An example given by Syncrude (Clarke 1999) is that average costs of production fell by approximately two-thirds due to a variety of innovations, ranging from new types of scoops for extracting the raw material to the substitution of pipelines for conveyor belts for transporting the ore. However, more recent comments by the president of Suncor (see Cattaneo 2002) suggest that extraction costs for oil sands will be higher than previously estimated.

28 Tilton and Landsberg (1999) is the source for all the information on the US copper industry.

29 This is called solvent extraction electrowinning. Not all mines adopted this technology. Some had closed permanently and others did not have favourable conditions for its use.

30 The total labour force also fell sharply after the 1970s due to mine closures and capital deepening. Real wages also fell due to removal of unions at some mines.

31 These are total costs net of stumpage fees, royalties, depreciation and a rate of return on investment.

32 The current provincial government is in the process of changing provisions of the *Forest Practices Code*.

33 These comments are more applicable to coastal logging than interior production and reflect a host of factors in addition to the supply of natural capital — for example, US/Canada exchange rates and the softwood lumber dispute with the United States.

34 Recall that fisheries were identified in an earlier section as a renewable natural resource industry that appears to be unsustainable.

35 These could include contingent valuation, hedonic and revealed preference techniques.

36 See, for example, the sustainability indices produced by the World Economic Forum in collaboration with the Yale Center for Environmental Law and Policy and Columbia University's Center for International Earth Science Information Network. Two of their recent reports are *2002 Environmental Sustainability Index* and *Pilot Environmental Performance Index*, available at: www.ciesin.org/indicators/ESI/ESI2002_21MAR02tot.pdf and www.ciesin.org/indicators/ESI/EPI2002_11FEB02.pdf. See also Jones et al. (2002).

37 Swinand's work can also be found in Gollop and Swinand (2001). See also Acharya (1998), Smith (1998) and Weaver (1998) for discussion of the theoretical issues involved in incorporating pollution into productivity estimates.

38 This implies using the services of the natural environment as a waste depository.

39 Ground-level ozone is an input of urban smog and is associated with adverse health effects. The GDP to ozone curve is relatively flat over the period, showing neither continual improvement nor decline.

40 The data also obscure regional and daily variations in air quality. Average ambient air quality does not reflect spikes in pollutants that may occur within a given day. Days of poor air quality are correlated with higher death rates from lung and heart disease, a higher incidence of asthma attacks and other adverse events. While likely not affecting aggregate productivity, these variations in ambient quality are most definitely a quality-of-life concern to individuals.

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