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PRODUCTIVITY MEASUREMENT WITH NATURAL CAPITAL

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Abstract/Résumé

Productivity measurement with natural capital

Traditional measures of multi-factor productivity (MFP) growth generally do not recognise natural capital as inputs into the production process. Since productivity growth is measured as the residual between output and input growth, it will pick up the growth in unmeasured inputs, which can lead to a bias. The purpose of this paper is to gain a better understanding of the role of natural capital for productivity measurement and as a source of economic growth. To this aim, aggregate economy productivity measures mostly from the OECD Productivity Database are extended by incorporating natural capital as an additional input factor into the production function. More specifically, this paper considers oil, gas and various minerals as natural capital inputs, drawing on data from the World Bank. Results suggest that failing to account for natural capital tends to lead to an underestimation of productivity growth in countries where the use of natural capital in production is declining because of a dwindling natural capital stock. In return, productivity growth is sometimes overestimated in times of natural resource booms, if natural capital is not taken into account as an input factor. The direction of the adjustment to productivity growth depends on the rate of change of natural capital extraction *relative* to the rate of change of other inputs. The extended framework also makes the contribution of natural capital to economic growth explicit. This can be useful for countries relying on non-renewable resources to better understand the need to develop other sources of growth, for example by investing in human or productive capital, to prepare for times when resources endowments become scarce. While the measurement of natural capital remains very incomplete, leaving out natural forests, water and soil, the measurement framework can readily be applied to more encompassing data on the natural capital stock, once it becomes available.

JEL classification: D24, Q56, Q3, O47, Q50

Keywords: multi-factor productivity, green productivity, natural capital stock, natural resource accounting.

Productivité multi-factorielle avec capital naturel

Des mesures traditionnelles de croissance de la productivité multi-factorielle, en générale, ne prennent pas en compte le capital naturel en tant que facteur de production. Comme la croissance de productivité est la différence entre la croissance de la production et des intrants, cette mesure sera biaisée dès qu'il y aura intrants non-mesurés, comme par exemple le capital naturel. L'objectif de ce papier est donc de mieux comprendre le rôle du capital naturel dans les mesures de productivité, et comme source de croissance économique. Ainsi, le papier enrichit des mesures de productivité à l'échelle de l'économie agrégée, pour la plupart extraits de la base de données de productivité de l'OCDE, en intégrant explicitement le capital naturel comme facteur de production. Plus spécifiquement, le papier considère le pétrole, le gaz naturel et des minéraux variés comme des éléments du capital naturel, en se servant des données de la Banque Mondiale. Les résultats suggèrent qu'ignorer le capital naturel a tendance à mener à une sous-estimation de la croissance de productivité dans les pays où l'utilisation du capital naturel est en déclin à causes des réserves en voie de disparition. En revanche, la croissance de productivité est parfois sur-estimée pendant des périodes d'une hausse des prix des ressources naturelles. La direction de la correction de la mesure de croissance de productivité dépend du taux de croissance relatif de l'extraction du capital naturel *par rapport* au taux de croissance des autres intrants. La mesure de productivité ainsi enrichie permet aussi de mesurer explicitement la contribution du capital naturel à la croissance économique. Ceci peut s'avérer très utile pour des pays dépendant des ressources naturelles non-renouvelables pour mieux comprendre leur besoin d'investir dans le capital humain ou productif pour se préparer pour des périodes de pénurie de leurs ressources naturelles. Même si la mesure de capital naturel utilisée dans ce papier reste très restreinte, ne prenant en compte ni les forêts vierges, ni l'eau ou le sol, le cadre proposé peut facilement être appliqué à des données plus complètes, dès qu'elles seront disponibles.

Classification JEL: D24, Q56, Q3, O47, Q50

Mots clés : productivité multifactorielle, productivité verte, stock de capital naturel, comptabilité des ressources naturelles.

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TABLE OF CONTENTS

PRODUCTIVITY MEASUREMENT WITH NATURAL CAPITAL	5
Introduction	5
A framework including the use of natural capital in productivity growth measurement	6
The data	8
Results	9
Conclusions and further steps.....	19
APPENDIX 1.....	20
APPENDIX 2.....	22
APPENDIX 3.....	23
APPENDIX 4.....	24
BIBLIOGRAPHY	26

Tables

1. Dataset summary table.....	9
2. Average productivity growth per year, with and without natural capital	10
3. Average productivity growth per year, with and without natural capital	11
4. Growth accounting results incorporating the natural capital stock.....	14

Figures

1. Difference between MFP growth adjusted for natural capital inputs and traditional MFP growth....	11
2. Difference in traditional MFP growth and MFP growth adjusted for natural capital use	12
3. Difference between traditional MFP growth and MFP growth adjusted for natural capital.....	12
4. GDP growth and contributions - Norway and United Kingdom	15
5. GDP growth and contributions - Australia and Russia.....	15
6. GDP growth and contributions - New Zealand	16
7. GDP growth and contributions - Mexico and Denmark	16
8. GDP growth and contributions in Chile	17
9. Long-term Growth Scenario with copper	18
10. Long-term growth scenario with copper.....	18

Boxes

1. The impact of copper on long-run growth scenarios in Chile	17
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PRODUCTIVITY MEASUREMENT WITH NATURAL CAPITAL

Nicola Brandt, Paul Schreyer and Vera Zipperer¹

Introduction

1. Common measures of economic performance do not fully account for the role of the environment in production. While income generated through the depletion of natural capital, such as minerals and fossil fuels, is captured in the value of Gross Domestic Product (GDP) and in profits, the role of natural capital as an input factor is generally ignored in traditional Multi-Factor Productivity (MFP) growth measures. The typical production function used in productivity analysis includes labour and produced capital as input factors, but not natural capital, although the extraction of subsoil assets contributes a considerable share to GDP in some countries.

2. Recognising natural capital as an input may change measured productivity growth and the assessment of the sources of economic growth. In addition, an explicit analysis of the role of natural capital in production is an important element to better understand the sustainability of economic development. Depleting natural capital often leads to higher economic growth in the short term, but this can only be sustained if a sufficient part of the associated revenues is used to build other assets, such as human or physical capital, to secure the economy's ability to generate income in the long run. To assess this ability it is important to measure the use of natural capital in production, such as fossil fuels, minerals and forests, along with produced capital such as infrastructure, machines and buildings, along with factors like the education and skills of the workforce (human capital) as well as the quality of institutions. Measuring the growth contribution of natural capital provides a clearer idea about the extent to which the growth contribution of other production factors or productivity growth would have to increase to maintain similar levels of output growth when the natural capital stock declines and hence also the possibility to use it in production.

3. It is important to note that the extended productivity growth measure presented in this paper accounts only for the use of domestic natural capital, not for an economy's contribution to the global depletion of natural capital. This is because the interest of the analysis in this paper lies in better understanding the role of natural capital for traditional MFP growth measures at the aggregate economy level, which are crucial for economic growth. This measure typically subtracts changes in labour and

1. Nicola Brandt and Vera Zipperer are members of the Economics Department of the OECD. Paul Schreyer is a member of the Statistics Directorate of the OECD. The authors owe thanks to Francisco M. Guillen from the *Instituto Nacional de Estadística y Geografía* of Mexico for providing data on produced capital stocks for Mexico and Ilya B. Voskoboynikov for providing productivity data for Russia. The authors would also like to thank Paul O'Brien, Artur Radziwill and participants of several internal OECD seminars for their useful comments and suggestions. The opinions expressed herein are those of the authors and do not necessarily reflect the opinions of the OECD. This research has been possible thanks to generous financial support from the Norwegian Government.

produced capital inputs from GDP growth. Since GDP measures value added, it does not include the value of imported natural capital, which is an intermediate good. Consequently, it would not be correct to consider imported natural capital as an input to the production of GDP. Only the income generated by extracting domestic natural capital, such as oil or minerals, contributes to GDP, and thus only domestic natural capital can be considered an input factor.

4. Natural capital in this study is valued with its private user cost to companies that extract natural capital or use it in other ways to generate income. It is thus treated like labour and produced capital in the analysis. The question being addressed is the efficiency with which producers use labour, produced and natural capital to generate income, given the prices which they face. In particular, prices do not necessarily reflect the social cost of using natural capital, which may be much larger in some cases. Given the importance of forests for biodiversity, climate stability, soil integrity and as a source of medication, the social value of living trees is likely to be much larger than the market price of their wood. The loss of this value that results from logging is thus not fully captured by the productivity data presented here. The productivity growth measure presented in this paper is in no way a measure of welfare. It is a measure of efficiency with which producers in the economy transform inputs into outputs given the prices that they face.

5. This paper is organised as follows. The first section spells out a production framework that integrates the use of natural capital in production, and describes the data. Section 2 presents empirical results. Section 3 draws conclusions and suggests possibilities to extend this research.

A framework including the use of natural capital in productivity growth measurement

6. Productivity growth is typically measured as the difference between output growth and the growth in factor inputs. Traditional measurement of MFP within the Solow residual framework is based on a production function that combines inputs from labour, L , and produced (as opposed to natural, non-produced) capital, K , to generate output. Typically, when measuring productivity for the aggregate economy, the output measure is real GDP, denoted by Y in what follows. The production process is thus described by $Y = f(K, L, t)$, where t is an index of time. Productivity growth is defined as the shift of the production function over time, allowing producers to obtain more output with the same amount of inputs. Productivity growth is equivalent to the difference between output and aggregate input growth. Weights for the growth of labour and produced capital correspond to their respective cost shares if producers maximize profits (or minimize costs) (see Appendix 1). Cost shares are equivalent to value added shares under perfect competition and constant returns to scale [for an overview see *e.g.* OECD (2001); Diewert and Nakamura (2007); Jorgenson (1995)]. Productivity growth can hence be described by the following:

$$\frac{d \ln MFP}{dt} \equiv \frac{\partial \ln f}{\partial t} = \frac{d \ln Y}{dt} - \left(\frac{wL}{\gamma'} \frac{d \ln L}{dt} + \frac{u_K K}{\gamma'} \frac{d \ln K}{dt} \right) \quad (1)$$

where $\frac{d \ln X}{dt}$ denotes the logarithmic rate of change of variable X with respect to time, equivalent to its growth rate, w is the wage rate and u_K the user cost of produced capital. Total resource costs are defined by $\gamma' \equiv wL + u_K K$. In what follows, the shorthand $\frac{d \ln Z}{dt}$ will be used to capture the combined rate of growth of inputs: $\frac{d \ln Z}{dt} \equiv \left(\frac{wL}{\gamma'} \frac{d \ln L}{dt} + \frac{u_K K}{\gamma'} \frac{d \ln K}{dt} \right)$.

7. While there are other ways to measure productivity growth, such as data envelopment analysis, parametric methods or econometric methods, the main interest of this paper lies in better understanding the effect of including natural capital into the traditional MFP measure, as this is frequently used for the analysis of economic growth and productivity at the aggregate economy level. Such measures are readily available in the OECD Productivity Database and can be relatively easily extended to demonstrate the

effect of integrating natural capital into traditional productivity measurement. It is important to understand to which extent commonly used productivity growth measures can change, once natural capital is included in the analysis.

8. Including natural capital into this framework requires an adjustment of the aggregate input measure. The input index is extended to include natural capital. The flow of natural capital inputs, such as minerals, oil, gas and coal, will be denoted by S , the vector of quantities of natural capital inputs, $S=(S_1, \dots, S_i, \dots, S_N)$, that are used in production. Through the inclusion of S , the role of natural capital is explicitly taken into account. As in the traditional framework, productivity growth can be measured as the difference of the growth rates of output and aggregate inputs. However, the set of inputs will now be augmented by the natural capital input S . It should be noted that natural capital input is measured differently from produced capital input. While it is relatively easy to measure the flow of natural capital services as the volume of natural capital extraction, the services of produced capital, such as machines and buildings, are more difficult to observe and their service flow is assumed to be proportional to the produced capital stock. This implies that the rate of change of capital services equals the rate of change of the capital stock. Capital services thus enter the productivity calculations as the rate of change of the stock of different asset classes weighted by their user cost shares (OECD, 2009), which add up to the rate of change of the aggregate capital services measure, K . Natural capital, in contrast, enters the productivity calculations directly as a flow measure, that is annual extraction of each natural asset.

9. To build an aggregate input growth measure, a price for natural capital inputs is needed. The (private) user costs for using natural capital is denoted by u_S , which may be explicit, such as license fees for exploiting a mine or using a stream to run a hydropower station, or implicit if the producer is an owner-user of a natural capital stock. In that case, u_S would be the private shadow price of using natural capital in production, or the reduction in the value of the natural capital stock that results from extracting one (further) unit of it. Appendix 2 discusses the conditions under which u_S is equivalent to the unit rent of natural capital input. S should be thought of as an aggregate of different types of natural capital inputs S_i ($i=1,2,\dots$) with user costs u_{S_i} . The total value of natural capital input is then $u_S S = \sum_i u_{S_i} S_i$ and the growth rate of the volume of natural capital input is $\frac{dlnS}{dt} = \sum_i \frac{u_{S_i} S_i}{u_S S} \frac{dlnS_i}{dt}$. Total input costs, γ , including natural capital, are defined by $\gamma \equiv wL + u_K K + \sum_i u_{S_i} S_i$. The productivity growth measure then becomes (see Appendix 1 for a derivation):

$$\frac{dlnGMFP}{dt} = \frac{dlnY}{dt} - \left(\frac{wL}{\gamma} \frac{dlnL}{dt} + \frac{u_K K}{\gamma} \frac{dlnK}{dt} + \sum_i \frac{u_{S_i} S_i}{\gamma} \frac{dlnS_i}{dt} \right) \quad (2)$$

10. Whenever it is available, MFP data is taken from the OECD Productivity Database, where the user cost of capital is derived ‘exogenously’ from estimates of its elements, namely the long-run rate of return, the depreciation rate and the price of investment goods (OECD, 2009). This user cost estimate multiplied by the capital stock, corresponds to the cost of capital services, which, together with labour costs, make up total costs $\gamma' \equiv wL + u_K K$ in the traditional framework. In the extended framework with natural capital, costs are considered to be larger, including also the costs of services from natural capital, $\gamma \equiv wL + u_K K + \sum_i u_{S_i} S_i$. The cost shares of both labour and capital will have to be scaled down to reflect the increase in total costs, when the traditional measure is adjusted to include natural capital. The difference between the growth in S and growth in the traditional input index, Z , comprising labour and capital, determines whether traditional MFP growth has to be adjusted upwards or downwards, as shown in Appendix 1. As there is no need to make any assumption regarding returns to scale or the degree of competitiveness of output markets to derive the MFP growth measure presented in the OECD Productivity Database, total costs γ' do not necessarily equal the value of GDP in this framework. Typically costs γ' are smaller than nominal GDP. One interpretation, which suits the extended framework with natural capital,

would be that there are unmeasured inputs, such as the natural capital stock. The fact that estimate of the user cost of natural capital is in most cases smaller than or equal to the difference between γ' and GDP in the OECD Productivity Database fits this idea nicely.

11. A simplified method is used to measure the user cost of produced capital for countries for which no data are available in the OECD Productivity Database. Namely, the cost share of produced capital is measured as the difference between nominal GDP and labour costs. Thus, MFP measurement relies on the assumptions of constant returns to scale and perfect competition in these cases, which implies zero residual profits. Hence, total costs are considered to equal GDP and the weights of inputs are measured as their income shares in GDP. Assigning all non-labour income to produced capital, obviously does not allow for unmeasured outputs and when they are present, their income would be included in the estimate of the cost (or income) of produced capital. In this case, total costs are not underestimated, but the share of produced capital in these costs is overestimated. Hence, in this case, only the cost share of capital needs to be adjusted downwards. The difference between the growth of produced and natural capital determines how productivity growth will have to be adjusted (Appendices 1 and 3).

GMFP growth for countries for which user cost of capital is calculated exogenously:

$$\frac{d\ln GMFP}{dt} = \frac{d\ln MFP}{dt} + \frac{u_S S}{\gamma} \left(\frac{d\ln Z}{dt} - \frac{d\ln S}{dt} \right) \quad (3)$$

GMFP growth for countries where user cost of capital is calculated endogenously:

$$\frac{d\ln GMFP}{dt} = \frac{d\ln MFP}{dt} + \frac{u_S S}{P_Y Y} \left(\frac{d\ln K}{dt} - \frac{d\ln S}{dt} \right) \quad (4)$$

12. These equations show in which ways standard measures of MFP growth can be biased when natural capital inputs are not considered. Essentially, when disregarding natural capital as an input factor, input growth is underestimated by the traditional MFP growth measure whenever the natural capital input, S , grows faster than traditional inputs (in the case of exogenous measurement of the cost of capital) or produced capital (in the case of endogenous measurement of the cost of capital). As a result, productivity growth is overestimated, given that productivity growth is the difference between output and input growth. Conversely, if the use of natural capital in production grows more slowly than the combined growth of labour and capital inputs, aggregate input growth is overestimated and productivity growth is therefore underestimated. The adjustment is more pronounced, the larger the cost share of natural capital, as this will increase the weight of natural capital in the aggregate input index.

The data

13. The analysis is conducted with aggregate economy data for a sample of OECD and a few emerging countries. This study covers 23 OECD countries, Russia and South Africa (Table 1). Where data are available, the OECD Productivity Database is used to retrieve MFP growth and costs estimates, as well as input and output data. As mentioned above, the user cost of capital is estimated directly in this database². National data sources are used for a range of countries, for which no data are available in the Productivity Database, *i.e.* for Chile, Mexico, Russia and South Africa. Russian estimates are taken from Voskoboynikov (2012). The estimates for Chile, Mexico and South Africa are OECD calculations based on national data. The timeframe of the analysis is 1985 – 2008 for some countries, shorter for countries

2. For a detailed description of the Productivity Database and methodology, see OECD (2001) and the corresponding website (<http://www.oecd.org/std/productivitystatistics>).

where consistent data were not available over the whole period. Table 1 describes the dataset in more detail.

Table 1. Dataset summary table

Variable	Source	Countries covered	Time period covered
MFP, GDP, labour, produced capital, wage share and user costs of capital	OECD Productivity database	AUS, AUT, BEL, CAN, CHE, DEU, DNK, ESP, FIN, FRA, GBR, IRL, ITA, JPN, KOR, NLD, NOR, NZL, PRT, SWE, USA	1985 – 2008
MFP, GDP, labour, produced capital, wage share	National Source	CHL, MEX ¹⁾ , RUS ²⁾ , ZAF	1991 – 2008
Natural capital data	World Bank	AUS, AUT, BEL, CAN, CHE, CHL, DEU, DNK, ESP, FIN, FRA, GBR, IRL, ITA, JPN, KOR, MEX, NLD, NOR, NZL, PRT, SWE, USA, RUS, ZAF	1985 – 2008
Natural capital rent	World Bank	AUS, AUT, BEL, CAN, CHE, CHL, DEU, DNK, ESP, FIN, FRA, GBR, IRL, ITA, JPN, KOR, MEX, NLD, NOR, NZL, PRT, SWE, USA, RUS, ZAF	1985 – 2008

1) Productivity data are calculated on the basis of a dataset kindly provided by the Instituto Nacional de Estadística y Geografía from Mexico.

2) Productivity data for Russia (1995 – 2009) were generously provided by Ilya B. Voskoboynikov. For more details on the dataset see the corresponding paper (Voskoboynikov, 2012).

14. The coverage of natural capital in this analysis is constrained by data limitations. Even though the World Bank's wealth dataset provides an important milestone for the creation of an international database on the production and use of natural capital, it is mainly focused on sub-soil assets. Specifically, the sub-soil assets covered in the dataset as well as in this analysis are oil, gas, bauxite, copper, lead, nickel, phosphate, tin, zinc, gold silver, iron ore, soft and hard coal. However, other types of natural capital which also contribute to the production process, such as water, soil, or renewable resources such as fish stocks, are not included in this analysis because data are not readily available.

15. Natural capital inputs are valued with their unit rent, which is the market price net of extraction costs. It can be shown that under the assumption of inter-temporarily optimal depletion of natural capital, the user cost of natural capital, *i.e.* the change in its value after depletion of one unit, equals its marginal resource rent that is the market price net of marginal extraction cost (Appendix 2). In this paper these user costs are approximated with measures of unit rents provided by the World Bank. However, while marginal extraction costs would be the relevant measure for unit rents, these are not readily available. The World Bank therefore approximates marginal with average extraction costs and this approach is followed in this paper for lack of better data.

Results

16. The adjustment of the traditional productivity growth measure depends on natural capital input growth relative to other input factors. This can be seen in Tables 2 and 3, where a noticeable adjustment to the traditional MFP growth measure can be observed for countries with significant natural capital endowments, such as Norway, Russia, Chile and Mexico and, to a lesser extent, the United Kingdom, Australia, Canada and the Netherlands. In Australia, Denmark, Norway, Finland and New Zealand the adjustment to the traditional MFP growth measure is negative, as natural capital grew faster on average over the sample period, than the traditional input index, combining labour and produced capital input growth only. In Australia, this was due to a strong generalised increase in minerals production, in Denmark and Norway to oil production and in New Zealand mainly to oil and gas production. By failing to account for a very fast-growing input factor, the traditional MFP growth measure overestimates productivity

growth in these countries. Contrary to what one might be tempted to think, though, it is not necessarily the case that the traditional MFP growth measure overestimates productivity growth in countries with resource booms. In fact, Tables 2 and 3³ show an upward adjustment of the productivity growth measure in Canada, Chile, Mexico, Russia and South Africa, all of which experienced a resource boom over recent years. This is because during resource booms not only natural capital grows very fast, but other factor inputs do as well. In particular, there is often an investment boom associated with resource booms, originating in the resource sector, but often spilling over to other parts of the economy. So even if natural capital inputs grow very fast during resource booms, other inputs may grow even faster. In that case, the productivity growth measure is adjusted upwards, once natural capital is taken into account.

Table 2. Average productivity growth per year with and without natural capital

Based on data from the OECD Productivity Database, 1986-2008¹

Country	Traditional MFP growth in %	MFP growth with natural resources in %	Difference in percentage points	Traditional inputs growth in %	Natural capital growth in %	Share of resource rent in total cost in %
AUS	0.92	0.88	-0.04	2.41	4.14	4.35
AUT	1.43	1.44	0.00	1.14	0.19	0.21
BEL	1.32	1.32	0.00	0.99	-20.00	0.00
CAN	0.38	0.42	0.04	2.26	1.51	3.97
CHE	0.06	0.06	0.00	1.42	-6.96	0.00
DEU	1.10	1.11	0.01	0.38	-1.00	0.19
DNK	0.75	0.72	-0.03	1.27	7.91	2.25
ESP	0.35	0.35	0.01	2.87	-10.52	0.06
FIN	2.07	2.07	-0.01	0.54	6.88	0.07
FRA	1.06	1.06	0.00	1.03	-6.15	0.05
GBR	1.26	1.33	0.08	1.43	-1.20	2.09
IRL	2.84	2.86	0.02	2.40	-7.05	0.34
ITA	0.45	0.45	0.00	1.20	0.19	0.21
JPN	1.46	1.46	0.00	0.53	0.63	0.02
KOR	3.93	3.93	0.00	2.47	-6.54	0.05
NLD	0.95	1.00	0.05	1.85	-0.69	1.83
NOR	1.18	1.02	-0.16	1.46	4.97	16.77
NZL	0.68	0.66	-0.02	1.78	2.11	1.41
PRT	1.29	1.29	0.00	1.17	-3.31	0.01
SWE	1.03	1.03	0.00	1.26	0.08	0.23
USA	1.03	1.05	0.02	1.84	-0.99	1.09

1. 1996-2007 for Austria, 1986-2004 for Belgium, 1991-2008 for Switzerland, 1992-2008 for Germany, 1986-2007 for the Netherlands, Denmark, United Kingdom, and 1996-2005 for Portugal.

17. The adjustment of the productivity growth measure is very likely positive, once natural capital endowments start to decline. Some countries, notably the United Kingdom, the United States and the Netherlands, experienced a decline in natural capital inputs over the sample period. This is because oil and gas reserves were dwindling already over the largest part of the period considered here. Productivity growth in these countries was stronger than the traditional MFP growth measure would suggest, because the failure to account for declining natural capital inputs leads to an overestimation of aggregate factor

3. Note that productivity growth measures in Tables 2 and 3 are not comparable because of differences in the measurement of produced capital stock/capital services (see OECD, 2009, for details).

input growth, which is equivalent to an underestimation of productivity growth. Since labour and capital generally tend to grow, save in very severe recessions, the adjustment will be negative when natural capital input growth is negative.

Table 3. Average productivity growth per year with and without natural capital

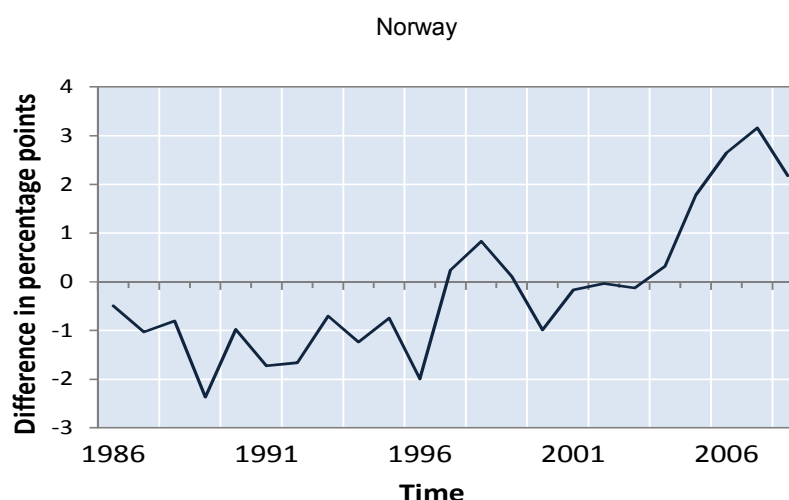
Based on national data, 1996 – 2008¹

Country	Traditional MFP growth in %	MFP growth with natural resources in %	Difference in percentage points	Capital stock growth in %	Natural capital growth in %	Share of resource rent in GDP in %
CHL	0.90	1.10	0.21	5.07	4.18	6.63
MEX	0.97	1.09	0.12	2.81	0.84	3.73
RUS	2.21	2.50	0.28	3.16	2.12	13.32
ZAF	1.62	1.70	0.07	2.01	0.65	2.35

1. 1997-2008 for Chile

18. The adjustment of the traditional MFP growth estimate may change over time, in particular when periods of resource scarcity follow resource abundance. This is the case for Norway (Figure 1). In the years up until 2000 when oil reserves were still relatively plentiful and the rate of extraction was fast, the use of natural capital grew faster than aggregate capital and labour inputs. As a result, the traditional MFP growth measure underestimates input growth in those years and productivity growth is overestimated. After 2000, however, as oil reserves in Norway became scarcer, the rate of oil extraction actually declined. Aggregate input growth is therefore overestimated if only labour and the capital stock are considered. As a result, the traditional MFP growth measure underestimates productivity growth.

Figure 1. Difference between MFP-growth adjusted for natural capital inputs and traditional MFP growth



19. The size of the correction has sharply increased over the most recent years of the sample period in many countries, owing to a strong and generalised increase in commodity prices. This is the case regardless of whether productivity growth is corrected upwards or downwards. Given that the data series for Russia and South Africa starts only in 1995, and is thus shorter than for the rest of the countries, the strong weight of the correction term in the last years of the sample period also magnifies the average correction of productivity growth in these two countries compared to others. In fact, the correction is

slightly negative on average between 1996 and 2004 in both Russia and South Africa, but much smaller than the positive correction after that (Figure 2). Another example is Norway (Figure 1). The sharp rise in oil and gas prices led to an increase in the share of natural capital rents in costs, thus magnifying the upward-correction of the traditional productivity growth estimate through the second term in equation (3). In New Zealand, the negative correction over the whole sample period is driven by strong spikes of oil and gas production in the last two years of the sample period, which are more strongly weighted than natural capital input developments in prior periods, owing to rising commodity prices (Figure 3). It is important to note that it is quite appropriate to give inputs a higher weight when their price increases. This is not specific to natural capital because it would be the same for labour or produced capital if their prices increased. Producers would normally respond to an increase in the relative price of one input by substituting some of it with other now relatively cheaper inputs. Thus the relatively more expensive input should be expected to grow more slowly because the relatively cheaper inputs would grow faster. Assigning a higher weight to the input that now grows more slowly avoids mistaking this factor substitution as a general decrease in factor input growth, which would be equivalent to mistaking it for technological progress.

Figure 2. Difference between MFP-growth adjusted for natural capital inputs and traditional MFP growth

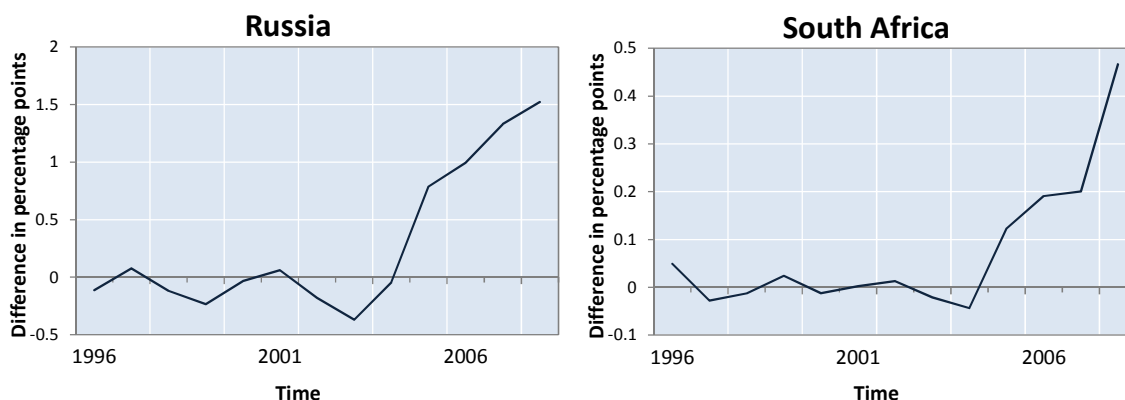
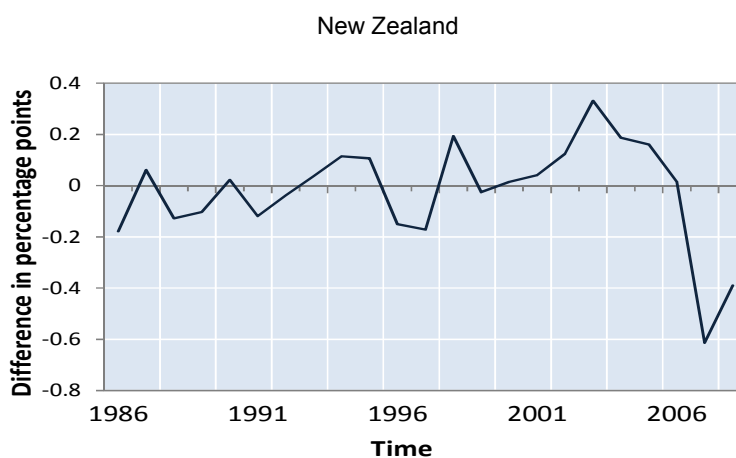


Figure 3. Difference between MFP-growth adjusted for natural capital inputs and traditional MFP growth



20. Overall, the growth contribution of natural capital is relatively small compared to other production factors. Even in resource-rich countries, the share of natural capital income in overall production costs is hardly ever higher than 5% (Tables 2 and 3). As a consequence, the growth contribution of natural capital rarely attains a quarter of a percentage point. There are only a handful of countries where the growth contribution of natural capital is significant, including Australia, Chile, Norway, and Russia (Table 4). Yet, in all cases it is much smaller than the contribution of labour and produced capital. Small though it may be, it is still useful to have a clear picture of the growth contribution of natural capital. In this context, it is also important to note that subsoil assets capture a small part of countries' natural capital stock, leaving out many other aspects, such as land, water, natural forests and renewable resources, such as fish stock. Another aspect is that this paper looks at user costs of natural capital from the producer perspective. The social costs of natural capital inputs may be much higher in some cases. One example would be forests, which offer valuable services, such as the absorption of CO₂, providing habitat to many species and ingredients for many medications. Finally, results in Table 4 show the growth contribution of natural capital only from an accounting perspective. While that can give some interesting insights, the overall impact of resource booms and busts on economic growth is often larger through their effects on investment and the reaction of productivity growth.

Table 4. Growth accounting results incorporating the natural capital stock

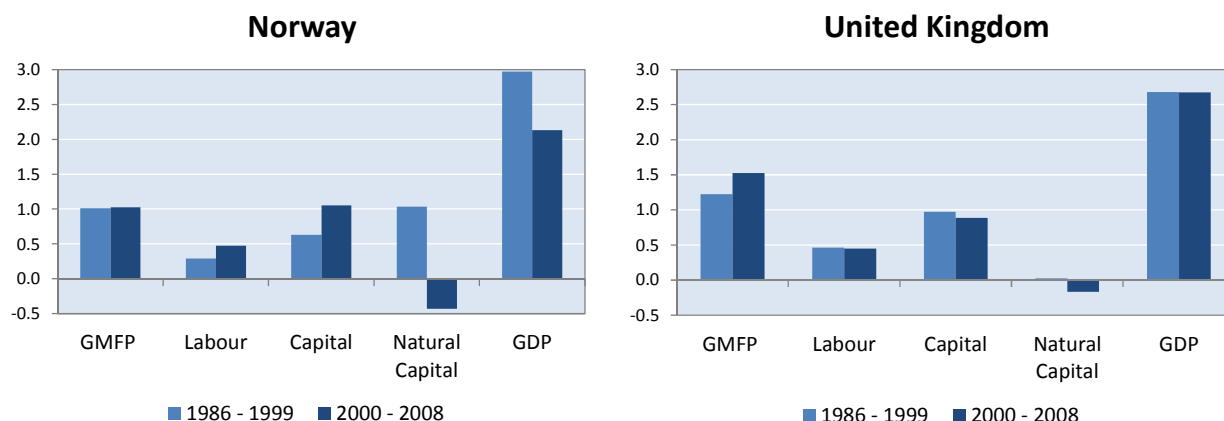
Country	1986-2008 ¹				
	MFP growth adjusted (natural resources) in %	GDP growth in %	Growth contribution of labour input in %	Growth contribution of capital input in %	Growth contribution of natural capital in %
AUS	0.88	3.34	1.26	1.05	0.15
AUT	1.44	2.60	0.57	0.57	0.00
BEL	1.32	2.28	0.24	0.75	0.00
CAN	0.42	2.67	1.11	1.06	0.05
CHE	0.06	1.46	0.60	0.82	0.00
CHL	1.10	4.09	0.81	2.04	0.14
DEU	1.11	1.48	-0.21	0.58	0.00
DNK	0.72	2.00	0.24	0.99	0.06
ESP	0.35	3.22	1.63	1.24	0.00
FIN	2.07	2.63	-0.04	0.58	0.01
FRA	1.06	2.08	0.31	0.71	0.00
GBR	1.33	2.68	0.46	0.94	-0.04
IRL	2.86	5.25	1.52	0.87	-0.01
ITA	0.45	1.64	0.39	0.81	0.00
JPN	1.46	1.99	-0.36	0.88	0.00
KOR	3.93	6.39	0.72	1.74	0.00
MEX	1.09	3.49	0.86	1.54	-0.01
NLD	1.00	2.78	0.99	0.83	-0.01
NOR	1.02	2.64	0.36	0.80	0.46
NZL	0.66	2.45	0.85	0.90	0.04
PRT	1.29	2.47	0.31	0.86	0.00
RUS	2.50	4.53	0.66	0.86	0.27
SWE	1.03	2.33	0.30	0.95	0.00
USA	1.05	2.84	0.94	0.89	-0.01
ZAF	1.70	3.61	1.00	0.93	-0.01

1. 1996-2007 for Austria, Mexico, Russia, South Africa, 1986-2004 for Belgium, 1991-2008 for Switzerland, 1992-2008 for Germany, 1986-2007 for the Netherlands, Denmark, United Kingdom, 1996-2005 for Portugal, 1997-2008 for Chile

21. Growth accounting with natural capital is also useful to study the changing role of natural capital during times of abundance and scarcity. This can provide important information regarding the sustainability of growth. Figure 4 shows how the growth contribution of natural capital changed over time in Norway and the United Kingdom. From the mid-1980s to 2000 the growth contribution of natural capital was relatively large in Norway. After that it turned negative, as oil reserves started to diminish. Although the growth contribution of other factors of production increased a little, GDP growth declined almost in tandem with the growth contribution of natural capital. One interpretation would be that during times of resource abundance Norway did not invest sufficiently in other forms of wealth, such as human or physical capital, that would maintain its ability to generate GDP growth at the same high level, for example through higher productivity growth. It should be noted, however, that Norway has been investing a good part of its natural capital revenues in a sovereign wealth fund that invests in foreign assets, thus transforming natural into financial capital for the benefit of future generations. The income generated from foreign assets does not contribute to GDP, but to national income (GNI). Yet, the average annual growth rate of GNI declined as much as the GDP growth rate over the two periods considered here, so taking the sovereign wealth fund into account does not change the picture described before. In the United Kingdom the growth contribution of natural capital was already very low during the first period. It then turned

negative after 2000. However, MFP growth picked up to compensate for this negative growth contribution of natural capital, and GDP growth stayed roughly the same. Again, one interpretation would be that the United Kingdom invested sufficiently in human or knowledge capital to compensate the (small) drag on growth from a negative contribution from natural capital.

Figure 4. GDP growth and contributions - Norway and United Kingdom



22. Growth accounting results suggest that the impact of resource booms on productivity and investment is important for an economy to benefit in terms of higher GDP growth. In Russia the resource boom that intensified towards the middle of the last decade was accompanied by an increase in both the produced capital stock growth and productivity growth (Figure 5). As a result, Russia benefitted through a substantial increase in GDP growth. In contrast, when comparing the same two episodes for Australia, it turns out that while the growth contribution of produced capital increased in the later period with a natural resource boom, productivity growth decelerated significantly. As a result, GDP growth actually declined. Likewise, New Zealand (Figure 6) did not benefit from higher GDP growth as a result of a higher growth contribution of natural capital and other factors of production over 2004-2008 compared to the earlier period, because productivity declined significantly at the same time, actually turning negative.

Figure 5. GDP growth and contributions - Australia and Russia

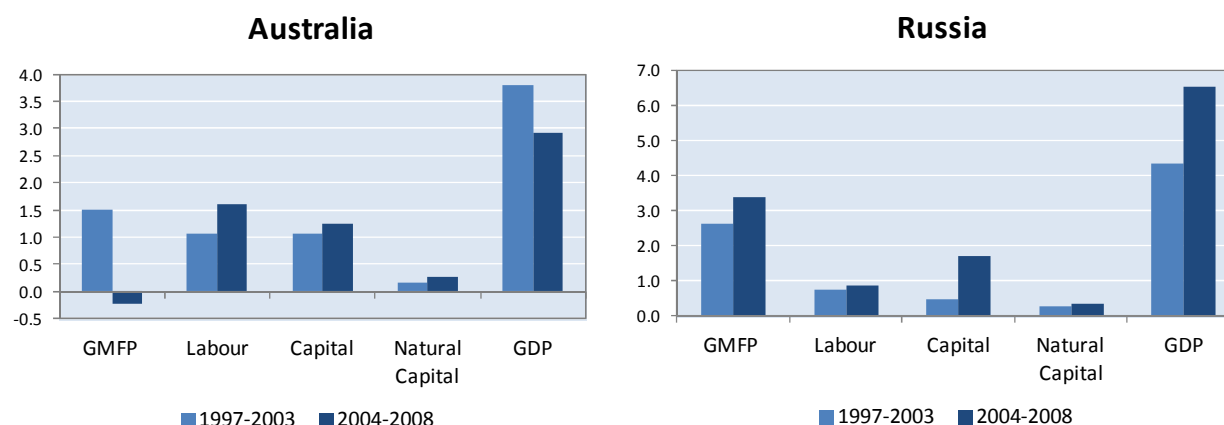
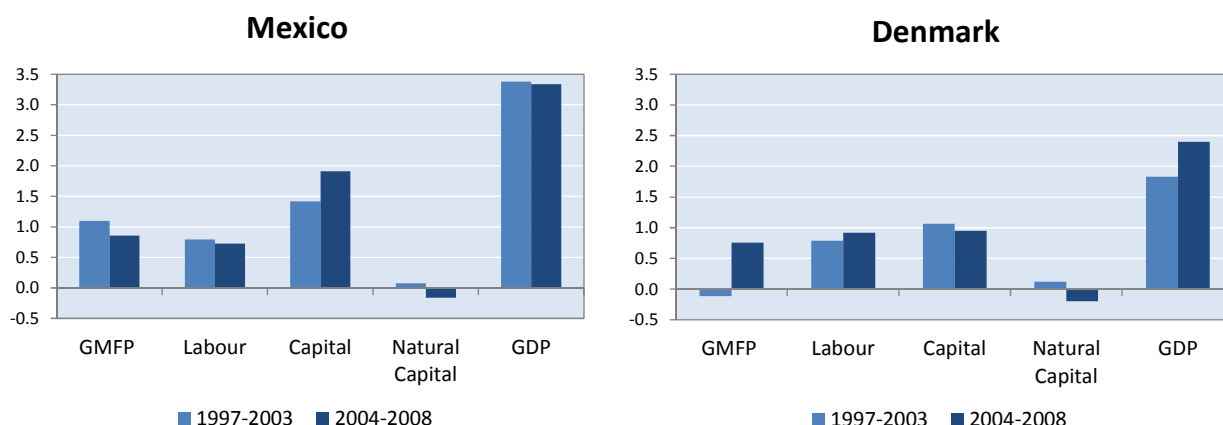


Figure 6. GDP growth and contributions - New Zealand



23. Some countries are able to compensate declining contributions of natural capital through higher productivity growth, or produced capital. This was the case for Denmark (Figure 7) when comparing 2004-2008 with 1997-2003. Mexico, in contrast, experienced a decline in productivity growth along with the decline in the growth contribution of natural capital, but was able to compensate both with higher growth contribution of the produced capital stock.

Figure 7. GDP growth and contributions - Mexico and Denmark

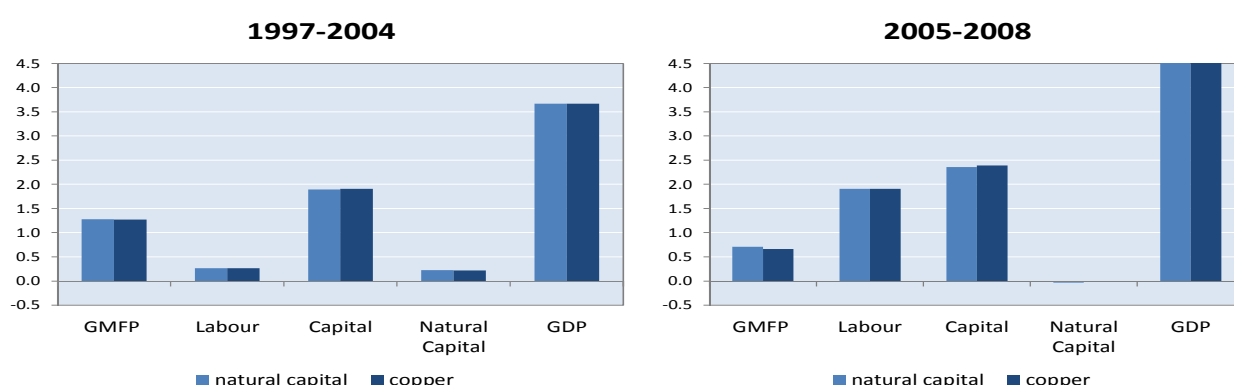


24. Chile is an interesting case to assess some of the potential uses of the framework presented in this paper. It is a basis to study the impact of different scenarios for natural capital use in production on long-term income developments. To this end it is useful to update the data used in this paper. While the World Bank's natural capital is available only until 2008, copper production data from national sources is available until 2011. Since copper makes up the lion's share of natural capital in Chile, looking at an extension of growth accounting that integrates the production of copper only, still gives important insights into the role of natural capital for long-term growth developments. The copper rent has accounted for 80% of the total natural capital rent on average since 1990 and for 90% since 2005, owing to the copper price boom. In fact, growth accounting results hardly change if only copper is considered as natural capital rather than the full set of natural capital assets considered in this paper (Figure 8). The growth accounting exercise based on copper shows that the growth contribution of copper has vanished since 2005. This owes

to bottlenecks related to declining copper content in ores and harder to reach reserves, along with energy and water scarcities. It is instructive to look at some scenarios for potential future developments of copper production to gain insights into the importance that this might have on Chile's growth path. The discussion in Box 1 shows that declining copper production might drag down expected economic growth to a considerable extent in Chile, unless the country is able to improve its productivity performance through productive investments in human and knowledge capital and further improvements in its conditions for competition and entrepreneurship. It should be noted, though, that it is impossible to predict future developments in copper production, as much depends on the success of exploration efforts to find new reserves and technological progress. What is described in Box 1 are merely illustrative scenarios.

Figure 8. GDP growth and contributions in Chile

With natural capital stock and with copper only



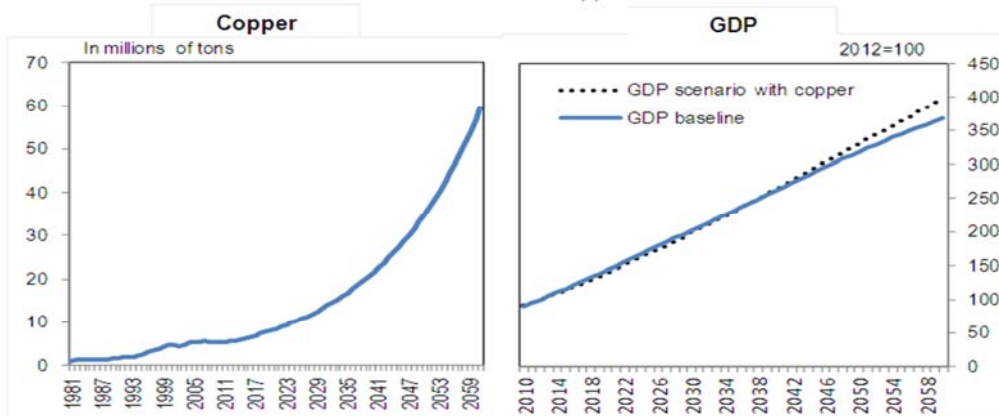
Box 1. The impact of copper on long-run growth scenarios in Chile

While it is extremely difficult to predict copper production in the long term, as much will depend on technology developments and the success of exploration efforts, it is illustrative to look at some scenarios and their effects on GDP developments for Chile.

The scenarios presented in here build on the OECD's long-term growth scenarios (Johansson et al., 2012). The production function used in that work is augmented here to include a natural capital stock (see Appendix 4). Since for Chile copper makes up the lion's share of natural capital inputs, the scenario presented here includes copper only for the sake of simplicity. Up to date data on copper production and rents is more readily available than some of the other elements of the natural capital stock as defined in this paper.

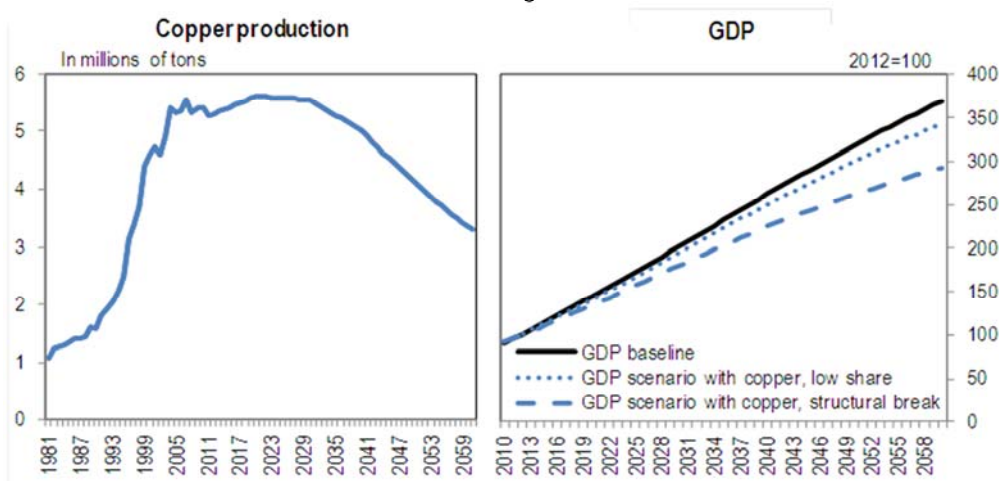
In a scenario in which copper production overcomes the current stagnation and continues to grow at the average rate observed since 1970, the expected growth path would be unaffected (Figure 9). In fact, starting around 2040, GDP would be higher under this scenario than under the baseline scenario, as continued copper production growth would offset some of the effects of the declining working age population.

Figure 9. Long-term Growth Scenario with copper
Scenario 1: continued copper boom



The picture looks different in a second scenario, in which copper production would continue to grow until 2020, then stagnate and start to decline after 2030. The developments until 2020 are based on expectations regarding the expansion of production capacity based on current investment plans. It should be noted, though, that these plans are behind target. In this scenario, GDP might be 20% below the level expected in the baseline scenario in 2060 (Figure 10), if the share of copper rents in GDP stays as high as it has been in recent years. The downward adjustment of GDP would be lower with a lower share of copper in GDP (for details regarding different assumptions regarding the share of copper rents in GDP see Appendix 4). The scenario for copper production does not seem unrealistic, given that the sector is already hitting bottlenecks. If Chile were to continue to extract copper at the current rate, proven reserves - that are known and can potentially be exploited with available technologies - would last another 35 years. Yet, new technologies and exploration tend to lead to discovery of new reserves and the possibility to exploit them, especially in times of scarcity and rising prices. It is thus likely that Chile will be able to exploit its copper reserves for much longer than what a simple calculation based on current proven reserves and extraction rates would suggest. On the other hand, assuming declining production at some point in the future, given the bottlenecks observed already today, has some validity.

Figure 10. Long-term growth scenario with copper
Scenario 2: hitting bottlenecks



Conclusions and further steps

25. When taking natural capital into account, the adjustment of traditional productivity growth measures is generally small, but this may change as more encompassing data becomes available. The growth contribution of natural capital is significant only for a handful of countries based on the data analysed in this paper. However, this partly reflects the fact that the natural capital data used in this paper is not very encompassing. Neither soil nor water are included, nor is wild fish stock. Moreover, the various services that the forest and other ecosystems provide to keep humans and other creatures alive are not captured, although this is the very basis of any economic activity. The contribution of this paper is to develop a methodology to include natural capital into traditional measures of productivity growth, which can be developed further, as better and more extensive data on natural capital becomes available. In 2012, the international community agreed on a new accounting standard for environment-economic data (SEEA). Implementation of the SEEA will make available more physical and monetary data on natural capital, in particular land, aquatic resources and freshwater.

26. Further insights might be gained by conducting this exercise at the industry level. The role of natural capital can obviously be attributed to the corresponding natural capital sectors, such as mining for energy and minerals. The growth contribution of natural capital in these sectors and their role for productivity growth will very likely be much greater than in the aggregate economy. An important future source of data for industry-level analysis will be data compiled in the framework of the System of Integrated Environmental Economy Accounts (SEEA) as it will be consistent with national accounts aggregates of inputs and outputs.

27. Although the framework presented in this paper is not designed to track environmental sustainability as such, it provides useful insights into the role of natural capital for national income over time and these feed into considerations on sustainability. Even if the contribution of natural capital to national income is relatively small, it is useful to make it explicit and understand just how much it contributes to increases in GDP. This will help researchers and policy makers better understand what happens when natural capital endowments become scarcer over time. In such cases, the growth contribution of natural capital will inevitably become smaller, often times even negative to disappear eventually. If countries that have exploited their natural capital want to maintain their GDP growth rates, this can happen only if the growth in productivity or other input factors increases at the same rate as the growth contribution of natural capital decreases, perhaps as a result of previous investments in human or knowledge capital. In that sense, a simple growth accounting exercise that explicitly takes into account the natural capital stock can contribute to a better understanding of the sustainability of economic development in resource-rich countries.

28. It should be noted, though, that the growth contribution of natural capital is captured only from an accounting perspective and in a very direct way. Indirect effects of natural resource booms and busts, for example on the formation of produced capital and on industrial production cannot be taken into account with the kind of framework presented here. The growth effects of natural resource booms and busts can of course be much larger than the direct effects from an accounting perspective, when all indirect impacts are taken into account.

29. The framework can also be used to study the impact of natural capital on income developments in the long run. Difficult though it may be to predict long-term developments for natural capital endowments and use in production, the impact of different scenarios for such developments on expected income can be studied with the framework presented in this paper, as demonstrated for the case of Chile. This would give policy makers and researchers a better understanding of productivity growth improvements that would be needed to make up for a potentially declining growth contribution of natural capital. The example presented for Chile could be extended to the full set of natural capital assets considered in this paper and to all resource-rich countries.

APPENDIX 1

1. To include natural capital into productivity measurement the traditional production function is extended to include the flows of natural capital used in production, $S=[S_1, S_2, \dots]$ which will in most cases correspond to natural resource extraction.

$$Y=F(K, L, S, t) \quad (A1.1)$$

with $F_K, F_L, F_{S_i} > 0, F_{KK}, F_{LL}, F_{SS_i} < 0$ ($i=1,2, \dots$) as first- and second-order partial derivatives of F.

2. Constant returns to scale in production are assumed, such that F is homogenous of degree one in K, L and S. Totally differentiating (A1.1) with respect to time and rearranging yields

$$\frac{d \ln GMFP}{dt} \equiv \frac{d \ln F}{dt} = \frac{d \ln Y}{dt} - \frac{F_L L}{Y} \frac{d \ln L}{dt} - \frac{F_K K}{Y} \frac{d \ln K}{dt} - \sum_i \frac{F_{S_i} S_i}{Y} \frac{d \ln S_i}{dt} \quad (A1.2)$$

where F_X denotes the derivative of function $F(X, \dots)$ with respect to its argument X.

3. If producers minimise costs, the marginal productivity of each input factor will equal its real input price as shown as follows:

$$\text{Min } \mathcal{L} = wL + u_K K + u_S S + \lambda(\bar{Y} - F(L, K, S, t)) \quad (A1.3)$$

With first order conditions for L, K, and S: $\frac{\partial \mathcal{L}}{\partial L} = w - \lambda F_L = 0$; $\frac{\partial \mathcal{L}}{\partial K} = u_K - \lambda F_K = 0$; $\frac{\partial \mathcal{L}}{\partial S_i} = u_{S_i} - \lambda F_{S_i} = 0$. Evaluating the Lagrange multiplier λ and using the assumption of linear homogeneity of F yields:

$$\gamma = wL + u_K K + u_S S = \lambda \left(F_L L + F_K K + \sum_i F_{S_i} S_i \right) = \lambda F = \lambda Y \rightarrow \lambda = \frac{\gamma}{Y} \quad (A1.4)$$

Given the valuation of λ and the first order conditions, it follows that the production elasticities of inputs equal their income share in total costs:

$$\frac{F_L L}{Y} = \frac{wL}{\lambda Y} = \frac{wL}{\gamma} \quad (A1.5)$$

$$\frac{F_K K}{Y} = \frac{u_K K}{\lambda Y} = \frac{u_K K}{\gamma} \quad (A1.6)$$

$$\frac{F_{S_i} S_i}{Y} = \frac{u_{S_i} S_i}{\lambda Y} = \frac{u_{S_i} S_i}{\gamma} \quad (A1.7)$$

4. Equation (A1.2) can thus be written as

$$\frac{d \ln GMFP}{dt} = \frac{d \ln Y}{dt} - \frac{wL}{\gamma} \frac{d \ln L}{dt} - \frac{u_K K}{\gamma} \frac{d \ln K}{dt} - \sum_i \frac{u_{S_i} S_i}{\gamma} \frac{d \ln S_i}{dt} \quad (A1.8)$$

5. Denoting total factor input costs in the traditional MFP framework by $\gamma' \equiv wL + u_K K$, it can be shown that the ratio between the traditional and the extended input cost measure is $\frac{\gamma'}{\gamma} = 1 - \sum_i \frac{u_{S_i} S_i}{\gamma}$. A shorthand measure $Z = Z(L, K)$ is used for the volume of aggregate of traditional labour and capital inputs where the growth rate of Z is given by

$$\frac{d \ln Z}{dt} \equiv \left(\frac{wL}{\gamma'} \frac{d \ln L}{dt} + \frac{u_K K}{\gamma'} \frac{d \ln K}{dt} \right) \quad (A1.9)$$

such that

$$\frac{d \ln MFP}{dt} = \frac{d \ln Y}{dt} - \frac{d \ln Z}{dt} \quad (A1.10)$$

6. Equation (A1.8) can then be rewritten as:

$$\begin{aligned} \frac{d \ln GMFP}{dt} &= \frac{d \ln Y}{dt} - \frac{\gamma'}{\gamma} \left(\frac{wL}{\gamma'} \frac{d \ln L}{dt} + \frac{u_K K}{\gamma'} \frac{d \ln K}{dt} \right) - \sum_i \frac{u_{S_i} S_i}{\gamma} \frac{d \ln S_i}{dt} \\ \frac{d \ln GMFP}{dt} &= \frac{d \ln MFP}{dt} + \left(1 - \frac{\gamma'}{\gamma} \right) \frac{d \ln Z}{dt} - \sum_i \frac{u_{S_i} S_i}{\gamma} \frac{d \ln S_i}{dt} \\ \frac{d \ln GMFP}{dt} &= \frac{d \ln MFP}{dt} + \sum_i \frac{u_{S_i} S_i}{\gamma} \left(\frac{d \ln Z}{dt} - \frac{d \ln S_i}{dt} \right) \end{aligned} \quad (A1.11)$$

7. This equation shows that the difference between the traditional MFP growth measure and the extended measure, including natural capital, will depend on the difference between the growth rate of the traditional composite input index, comprising labour and produced capital only, and the growth in the use of natural capital S , as well as on the share of natural capital rents in production.

APPENDIX 2

1. The optimal extraction of a non-renewable capital stock $N(t)$ over a lifetime T , which is depleted at the quantity $S(t)$ in period t follows:

$$\max_{S(a)} V(t) = \int_t^{T-t} R_S(a, S(a), N(a)) e^{-r(a-t)} da \quad (\text{A2.1})$$

Given $\dot{N} = -S(t)$.

$V(t)$ is the net present value of resource rents, $R_S(t, S(t), N(t))$, which corresponds to the revenues from natural capital extraction net of costs $R_S = P_S S(t) - C_S(S(t), t)$, where total costs, C_S , include a normal return. P_S is the market price at which the extracted natural capital can be sold and r is a nominal interest rate. To keep things simple, it is assumed that resource rents do not depend on the remaining stock of natural capital, N . The present value Hamiltonian for this optimization problem is:

$$H(S(t), \lambda(t)) = R_S(t, S(t)) - \lambda(t)S(t) \quad (\text{A2.2})$$

The static efficiency condition then requires:

$$\frac{\partial H}{\partial S} = \frac{\partial R_S}{\partial S} - \lambda(t) = 0 \quad (\text{A2.3})$$

2. Because $\lambda(t)$ is the shadow cost of using (depleting) one unit of the capital stock, in terms of the associated change of the present value of resource rents, it can be interpreted as the user cost of the natural capital, u_S . In the case of unit extraction costs that are independent of the level of extraction $\frac{\partial C_S}{\partial S} = \bar{c}_S(t)$, resource rents can be expressed as $R_S(t, S(t)) = P_S(t)S(t) - C_S(S(t), t) = P_S(t)S(t) - \bar{c}_S(t)S(t)$, in which case equation (A2.3) states that the user cost of the natural capital equals its unit rent $\frac{\partial R_S}{\partial S} = \frac{R_S}{S} = P_S(t) - \bar{c}_S(t) = u_S(t)$. In that case, user costs can be measured as the surplus market price of the natural capital, P_S , over extraction costs. This is the World Bank method applied in this paper.

APPENDIX 3

1. For some countries, where data necessary to estimate the user costs of capital directly is difficult to find, MFP growth estimates are based on the assumption that all non-labour income accrues to capital and hence the user cost of capital is calculated as a residual. In this case, the natural capital rents are picked up by the cost share allocated to produced capital K . As a consequence, the cost share of capital is overstated if indeed some of this income accrues to natural capital instead. This implies that the user cost as measured in this framework is actually composed of two parts, the true user cost of produced capital and the user cost of natural capital: $u'_K K = u_K K + \sum_i u_{S_i} S_i = P_Y Y - wL$. Total input costs are equal to value added, because this measurement framework relies on the assumptions of constant returns to scale and perfect competition, which implies zero profits. In that case equation (1) from the main text can be written as

$$\frac{d \ln MFP}{dt} = \frac{d \ln Y}{dt} - \left(\frac{wL}{P_Y Y} \frac{d \ln L}{dt} + \frac{u'_K K}{P_Y Y} \frac{d \ln K}{dt} \right) \quad (A3.1)$$

Using $u'_K K = u_K K + u_S S$, equation (A3.1) can be rewritten as

$$\frac{d \ln MFP}{dt} = \frac{d \ln Y}{dt} - \left(\frac{wL}{P_Y Y} \frac{d \ln L}{dt} + \frac{u_K K}{P_Y Y} \frac{d \ln K}{dt} + \sum_i \frac{u_{S_i} S_i}{P_Y Y} \frac{d \ln K}{dt} \right) \quad (A3.2)$$

Given zero profits, $\gamma = P_Y Y$, equation (A1.4) can be written as

$$P_Y Y = wL + u_K K + u_S S = \lambda(F_L L + F_K K + F_S S) = \lambda F = \lambda Y \rightarrow \lambda = \frac{P_Y Y}{Y} \quad (A3.3)$$

The elasticities of the inputs can be rewritten as $\frac{F_L L}{Y} = \frac{wL}{P_Y Y}$, $\frac{F_K K}{Y} = \frac{u_K K}{P_Y Y}$, $\frac{F_S S}{Y} = \frac{u_S S}{P_Y Y}$. The equation for the adjusted MFP measure is then given by:

$$\frac{d \ln GMFP}{dt} = \frac{d \ln Y}{dt} - \frac{wL}{P_Y Y} \frac{d \ln L}{dt} - \frac{u_K K}{P_Y Y} \frac{d \ln K}{dt} - \sum_i \frac{u_{S_i} S_i}{P_Y Y} \frac{d \ln S_i}{dt} \quad (A3.4)$$

2. Which is equivalent to equation (A1.8) remembering that nominal GDP equals total costs in the framework described in this appendix, $P_Y Y = \gamma$. Comparing (A3.4) with equation (A3.2) yields:

$$\frac{d \ln GMFP}{dt} = \frac{d \ln MFP}{dt} + \sum_i \frac{u_{S_i} S_i}{P_Y Y} \left(\frac{d \ln K}{dt} - \frac{d \ln S_i}{dt} \right) \quad (A3.5)$$

This shows that in this framework, the difference between the traditional MFP growth measure and the measure including the natural capital stock, depends on the difference between the growth rate of natural capital and produced capital services and the share of natural capital rents in GDP. This equation is used to calculate the adjusted MFP growth measure for countries where the user cost of capital is calculated as a residual, i.e. Chile, South Africa, Mexico and Russia.

APPENDIX 4

1. The long-term growth scenarios developed in Johansson *et al.* (2013) are based on a Cobb-Douglas production function with constant returns to scale featuring produced physical capital, human capital, labour and Harrod-neutral technical progress according to:

$$Y = K^\alpha (AhL)^{1-\alpha} \quad (\text{A4.1})$$

where Y , K , A , h and L denote output, physical capital, the productivity level, human capital per worker and employment. The share of capital is set equal to 1/3. Scenarios until 2060 for all factor inputs and for A are then developed as described in Johansson *et al.* (2013). A long-term scenario for GDP is then derived with these elements and the production function described in equation (A4.1).

2. To develop long-term growth scenarios taking copper production explicitly into account, the notion of the capital stock is extended to include both produced capital, K , and the use of the natural capital stock, S .

$$Y = K^{\alpha-\beta} S^\beta (AhL)^{1-\alpha} \quad (\text{A4.2})$$

where S is the use of the natural capital stock for a given period and β is the share of natural capital rents in GDP. In the scenarios presented here for Chile S corresponds to copper production and β to the share of copper rents in GDP. The World Bank data is updated with copper production, price and unit cost data from the Chilean Copper Commission, Cochilco. Since Cochilco's unit cost data displays much higher unit cost inflation than the World Bank data in the 2000s, which has been derived by assuming cost increases in line with a manufacturing price index, the World Bank unit cost data was recalculated starting with the year 2000 by assuming unit cost increases in line with Cochilco's data after that.

3. The share of copper rents was relatively stable until 2004 around 3% and increased substantially thereafter to an average of more than 10% over 2005-2011. Therefore, two different assumptions were used for the scenarios. One assumption is that β remains stable at 3.2%, the average share of the copper rent in GDP before 2005. Another assumption is that there is a structural break in 2005, with β jumping to the post-2005 average of the copper share in GDP of 10.85%. A constant share of copper rents seems a reasonable assumption. While prices for copper should be expected to rise substantially, should scarcities arise in the future, so would unit costs, as extraction becomes more difficult and costlier. Thus, assuming a constant unit rent, that is prices net of extraction costs, seems reasonable, whether or not considerable scarcities are expected over the horizon for projections.

4. To derive new scenarios that take the hypothetical developments for copper explicitly into account, the scenarios for labour, human capital per capita and the produced capital stock are taken from Johansson *et al.* (2013). A new level for A is derived by solving equation A4.2 for A and using the data from Johansson *et al.* (2013) to derive a new time series for years until 2011.

$$A = \frac{Y^{\frac{1}{1-\alpha}}}{K^{\frac{\alpha-\beta}{1-\alpha}} S^{\frac{1}{1-\alpha}} hL} \quad (\text{A4.3})$$

5. The productivity series is then projected forward to 2060 by using the productivity growth rates implied in the series derived in Johansson *et al.* (2010). This seems sensible, because productivity scenarios in that exercise were derived with a convergence equation that specifies the speed of

convergence of actual productivity to its country-specific frontier. Both the speed of convergence and the country-specific frontier depend on institutions, such as the stringency of product market regulation and the openness of an economy (Johansson, 2013). While this is a sound analytical framework, it does not take into account that traditional MFP measures might also be influenced by the developments of natural capital inputs. In that sense, Johansson *et al.* (2010) have effectively derived a productivity growth series that is already net of any possible effects of natural capital and therefore their series does not need any further adjustments for the exercise considered here.

6. Different scenarios for copper production are then considered. In a first scenario, copper production would grow at its average growth rate observed since 1970, 4.98%, which is much higher than what has been observed over the past few years. In a second scenario, copper production would also resume growth starting in 2013 so that production reaches its expected capacity based on current investment plans in 2020. Copper production would then start to decline, first slowly and then more rapidly. As a result, copper production would reach a level in 2060 last seen in the mid-1990s.

7. These copper production scenarios, along with the scenario for productivity, A, described above and scenarios for other input series taken from Johansson *et al.* (2013) are then used to derive a scenario for long-term GDP developments. Results are discussed in Box 1 in the main text.

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