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Natural Capital and Wealth in the 21st Century

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Extending the wealth accumulation model of Piketty and Zucman [2014] to include net depreciation in fossil fuels, minerals, and forests produces two key indicators: the net national saving rate adjusted for natural capital depreciation, and the ratio of this rate to long-run growth. These indicators are applied to eight rich economies over 1970–2013 and developing countries for 1979–2013. Whereas in developing economies capital accumulation has largely kept pace with rising natural capital depletion, in the rich countries adjusted net savings have fallen to converge with the rate of natural capital depreciation, suggesting less compensation by net increases in other capital.
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INTRODUCTION

An important contribution of Thomas Piketty's book *Capital in the Twenty-First Century* [2014] is to document the rise in the wealth–income ratios over 1970–2010 for eight high-income economies—the United States, Japan, Germany, France, the United Kingdom, Italy, Canada, and Australia. For each of these countries, the wealth–income ratio has increased from 200–300 percent in 1970 to 400–600z in 2010. More extensive analysis of these ratios is provided by Piketty and Zucman [2014, henceforth PZ], who also develop a wealth accumulation model to explain the observed capital–income trends.

To construct these ratios for 1970–2010, PZ use official national accounts for each country, following the U.N. System of National Accounts (SNA). Wealth is defined conventionally as market-value "national wealth," which can be decomposed into domestic capital (including land and real estate) and net foreign assets.[1] Income is "net-of-depreciation national income," which is the sum of gross domestic product and net foreign income, less any domestic capital depreciation. Similarly, the national saving flow that adds to wealth is also measured net of capital depreciation. Finally, to explain the return to the high wealth–income ratios over 1970–2010 for the eight richest economies, PZ develop a variant of the constant-savings rate neoclassical growth model of Solow [1956] and Swan [1956], and establish that the long-run capital–income ratio β is equal to the (net) national savings rate s divided by the growth rate g in (net) national income.

However, the SNA approach to national accounts does not include the depreciation in natural resources essential to domestic production and income, such as fossil fuels, minerals, and forests. These resources are important sources of "natural" capital, and the value of their net depletion should also be deducted from annual income and savings [Arrow et al. 2012; Hamilton and Clemens 1999; Hartwick 1977 and 1990; Solow 1986; World Bank 2011]. The rationale is intuitive: if we use up more of energy, mineral, and forest resources to produce additional economic output today, then we have less natural capital for production tomorrow; thus, net national income and savings today should also account for any natural capital depreciation.

In this paper, I make two additional contributions to PZ's analysis of wealth–income ratios over 1970–2010.

First, I show that their one-good wealth accumulation model can be extended to allow for natural capital depreciation, although I develop this model using standard intertemporal optimizing behavior rather than assuming a constant (net) savings rate. This extension leads to two key indicators: the net national saving rate adjusted for natural capital depreciation s_t^* indicates the annual change in wealth (inclusive of natural capital) relative to net national income (adjusted for natural capital depreciation); and the ratio of this saving rate with respect to the long-run average annual growth in adjusted net national income per capita $s_t^*/\bar{g}^*$ indicates how annual changes in adjusted net wealth relative to income compare with long-run growth over some defined time period of T years.

Second, using data from the World Bank [2016], I apply these two indicators to examine the impacts of depreciation of key natural resources, such as fossil fuels, minerals, and forests, on the accumulation of adjusted net wealth over 1970–2013 for the eight largest economies analyzed by PZ and also Piketty [2014]. For comparison, I examine trends over 1979–2013 in s_t^* and $s_t^*/\bar{g}^*$ for low- and middle-income economies.

The main findings are that, although over the past four decades the rate of natural capital depreciation has been on average five times larger in developing countries than in the eight rich countries, in low- and middle-income economies other forms of capital investments have largely compensated for the rising natural capital depletion that has occurred since the late 1990s. In contrast, in the rich countries, the rate of adjusted net savings has converged to the rate of natural capital depreciation. As documented by PZ, over the past 40 years there may have been substantial accumulation of wealth relative to income in these economies, but as this accumulation has proceeded, natural capital depreciation is being compensated less and less each year by net increases in other forms of capital. The overall implications are that, given that stocks of natural resources are depleted for current production and wealth accumulation, a measure of national wealth that excludes natural capital depreciation likely exaggerates the actual increase in an economy's wealth over time, especially in those countries where accumulation of other forms of wealth is failing to compensate for diminishing natural capital.

THE ADJUSTED ONE-GOOD WEALTH ACCUMULATION MODEL

Because official SNA statistics do not routinely account for changes in stocks of natural capital – even fossil fuels, minerals, forests, and similar natural resources that can be bought and sold on markets – it is difficult to measure directly long-run trends in the natural capital/national income ratio for an economy. However, it is possible to indicate how natural resource depreciation affects wealth accumulation, through extending PZ's one-good wealth accumulation model to allow for such depreciation in the context of intertemporal optimizing behavior. The details of this extension are provided in the appendix.

Following PZ, let W_t denote the market value of national wealth at time t, and S_t is the net national savings flow between time t and t + 1. In the absence of any capital gains or losses between t and t + 1, wealth accumulation is simply $W_{t+1} - W_t = S_t$.[2] If Y_t is the net national income (i.e., national income less domestic capital depreciation) at time t, then the corresponding net national saving rate in the economy is $s_t = S_t/Y_t$ and the ratio of wealth (or capital) to income is $\beta_t = W_t/Y_t$.

Suppose that, in addition to W_t, an economy also contains a stock of available natural resources for production, with market value at time t of $\tilde{N}_t \geq 0$. The total wealth of the economy at time t is therefore $W_t^* = W_t + \tilde{N}_t$. As wealth now includes an endowment of natural capital, both net national income and net national savings in time t should be adjusted for any depreciation of natural capital depletion through its use in production over t and t + 1, net of any changes in the endowment due to new discoveries over the year and also renewable resource growth (see appendix). I refer to this modification of PZ's definition of wealth W_t^* as *adjusted net wealth.*

Let Y_t^* and S_t^* represent the adjustments to net national income and savings for any natural capital depreciation, respectively. It follows that the accumulation in adjusted net wealth between t and $t+1$ is

$$W_{t+1}^* - W_t^* = S_t^*.$$

Dividing both sides by adjusted net national income Y_t^* yields

$$\frac{W_{t+1}^* - W_t^*}{Y_t^*} = \frac{\Delta W^*}{Y_t^*} = s_t^*, \tag{1}$$

where $s_t^* = S_t^*/Y_t^*$ is the net national saving rate adjusted for natural capital depreciation, or the *adjusted net saving* rate. As Equation (1) states, s_t^* is an indicator of the annual change in wealth (inclusive of natural capital) relative to net national income (adjusted for natural capital depreciation).[3]

The saving rate s_t^* can also be expressed as a ratio with respect to the long-run average annual growth in adjusted net national income per capita. For any period of T years, the latter growth rate is $\bar{g}^* = \frac{1}{T}\sum_{t=0}^{T-1}\frac{\Delta Y_t^*}{Y_t^*}$. Consequently,

$$\frac{s_t^*}{\bar{g}^*} = \frac{\Delta W^*/Y_t^*}{\bar{g}^*}. \tag{2}$$

The ratio indicates how annual changes in adjusted net wealth relative to income compare with the average annual income growth per capita over some defined time period of T years. For example, if this growth rate is 2 percent per year, and adjusted net saving is 10 percent, then the rate of adjusted net wealth accumulation each year is 500 percent of long-run growth. However, if the adjusted net saving rate falls to 4 percent, then the rate of annual wealth accumulation relative to income is only 200 percent of $\bar{g}^*$.

Note that condition (2) should not be confused with the balanced growth outcome employed by PZ in their version of the Solow–Swan model. In the long run, with a fixed net saving rate $s_t = s$ and a balanced growth rate for Y_t of $g_t = g$, PZ show that the capital–income ratio β_t of an economy should converge to an equilibrium level, i.e.,$\beta_t \to \beta = \frac{s}{g}$.[4] In contrast, condition (2) makes no assumption about an economy attaining a balanced growth path; it is a simple ratio that depicts, over a defined period of T years, how the annual rate of net wealth accumulation compares to long-run growth over that period. Nevertheless, as shall be shown next, if there is a discernible trend in the $s_t^*/\bar{g}^*$ ratio, it does indicate whether or not adjusted net wealth is accumulating relative to increases in income in economies.

MEASURES OF n_t^*,s_t^*, AND $s_t^*/\bar{g}^*$

The World Bank's World Development Indicators contain time series of the value of net natural resource depletion, net national saving rates, and adjusted net national income from 1970 to 2013 for most countries of the world [World Bank 2016]. Using these data, I construct measures of s_t^* and $s_t^*/\bar{g}^*$ over this period for the eight countries analyzed by Piketty [2014] and PZ – the United States, Japan, Germany, France, the United Kingdom, Italy, Canada, and Australia.

The World Bank defines the value of net natural resource depletion as the sum of net forest, fossil fuel, and mineral depletion.[5] Net forest depletion is unit resource rents times the excess of roundwood harvest over natural growth. Energy depletion is the ratio of the value of the stock of energy resources to the remaining reserve lifetime (capped at 25 years). It covers coal, crude oil, and natural gas. Mineral depletion is the ratio of the value of the stock of mineral resources to the remaining reserve lifetime (capped at 25 years). It includes tin, gold, lead, zinc, iron, copper, nickel, silver, bauxite, and phosphate.

The World Development Indicators (WDI) provide annual estimates over 1970–2013 of the World Bank's aggregate value of net natural resource depletion as a percentage of gross national income (GNI) for the eight high-income countries. Converting this estimate to natural resource depletion as a share of adjusted net national income (constant 2005 \$), which is GNI minus consumption of fixed capital and natural capital depreciation, serves as my proxy measure of the rate of natural capital depreciation. I denote this *natural capital depreciation rate* as n_t^*. My approach to estimating n_t^* is to multiply the WDI's annual measure of net natural resource depletion as a percentage of gross national income (GNI) by its measure of GNI (constant 2005 \$), and then dividing the result by the WDI's annual estimates of adjusted net national income (constant 2005 \$).

Annual net national savings, which are gross national savings less the value of consumption of fixed capital, are also calculated as a percentage of GNI in the WDI. Estimating s_t^*, or the *adjusted net savings rate,* requires first adjusting the annual net national savings rate for natural capital depreciation as a share of GNI, multiplying by GNI (constant 2005 \$), and then dividing by adjusted net national income (constant 2005 \$). Finally, the average annual growth of adjusted net national income per capita over 1970–2013, which is already estimated in the WDI, serves as the measure of $\bar{g}^*$.

Figure 1 depicts the estimates of s_t^* and n_t^* averaged across the eight high-income economies over 1970–2013. The adjusted net savings rate for these countries declined considerably during these four decades. It was around 13 percent in the early 1970s but then fluctuated between 4 and 8 percent from the 1980s onwards. The savings rate fell to a low point of 1 percent during the Great Recession, but since 2011 has recovered to 2.5 percent. On average from 1970 to 2013, s_t^* was 6.9 percent. In contrast, natural capital depreciation has remained between 1 and 2 percent of adjusted net national income for most of the past 40 years. Thus, it appears that s_t^* and n_t^* have been converging for the eight richest economies in the world (see Figure 1). The long-run fall in the adjusted net savings rate indicates that there is less accumulation of other forms of capital each year to compensate for ongoing natural capital depreciation. This explains why the overall annual accumulation in adjusted net wealth relative to income for these economies, i.e.,$\Delta W^*/Y_t^*$, has been trending downwards since the 1970s.

Figure 2 shows the estimate in $s_t^*/\bar{g}^*$ averaged for the eight richest economies over 1970–2013. For illustrative purposes, the figure also includes PZ's estimated trend in the

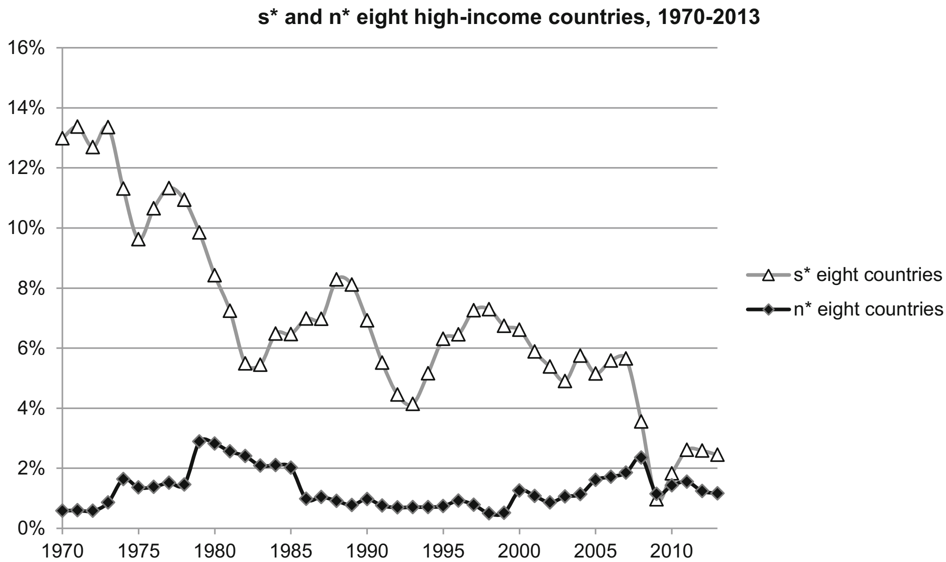

Figure 1. Adjusted net saving and natural capital depreciation in eight rich countries, 1970–2013. The eight countries are the United States, Japan, Germany, France, United Kingdom, Italy, Canada, and Australia. The data are based on the World Development Indicators [World Bank 2016]. The measure of s^* is gross national savings less the value of consumption of fixed capital and the value of net natural resource depletion as a percent of adjusted net national income (constant 2005 US$); the measure of n^* is annual value of net natural resource depletion as a percent of adjusted net national income (constant 2005 US$). Over 1970–2013, the average s^* for these eight countries was 6.9 percent, and average n^* was 1.3 percent. The margin of error (95 percent confidence level) associated with the sample mean for s^* and n^* was 3.3 and 1.0, respectively. An online technical appendix that indicates the data for individual countries underlying the trends depicted in this figure is available at http://www.edwardbbarbier.com/Projects/Nature_Capital_and_Wealth_in_the_21st_Century/OTA.html.

(conventional) capital–income ratio $\beta_t = W_t/Y_t$ averaged for these countries over 1970–2010. Finally, Figure 2 also includes the average $s_t^*/\bar{g}^*$ ratio over the four decades.

The trend in β_t depicted in Figure 2 confirms PZ's finding that the capital–income ratio for the eight wealthiest countries has increased steadily over 1970–2010. In 1970, their average capital–income ratio was around 340 percent (i.e., more than 3 years) of national income, and has risen to 525 percent (more than 5 years) of national income in 2010.[6]

In contrast, the $s_t^*/\bar{g}^*$ ratio for these countries displays a distinctly downward trend. In the early 1970s, this ratio was around 800 percent, which suggests that the annual rate of adjusted net wealth accumulation was more than 8 times the long-run average growth rate for the eight countries over 1970–2013. But since 2008, the $s_t^*/\bar{g}^*$ ratio has fallen well below 200 percent, which indicates that the rate of adjusted net wealth accumulation each year has been less than twice the growth rate. On average over 1970–2013, $s_t^*/\bar{g}^*$ was 415 percent, i.e., the rate of adjusted net wealth accumulation each year was four times the long-run growth.

The falling trends in s_t^* and $s_t^*/\bar{g}^*$ depicted in Figures 1 and 2 indicate that the rate of net national saving adjusted for natural capital depreciation has declined even faster than any slowdown in long-run growth in the eight rich countries from 1970 to 2013. This could have implications for long-run adjusted net wealth relative to income in these countries. For example, it is possible that the decline in $s_t^*/\bar{g}^*$ over the past four decades in the eight countries will continue into future years. If so, the rate of net wealth accumulation relative to growth will continue to fall well below the average rate of

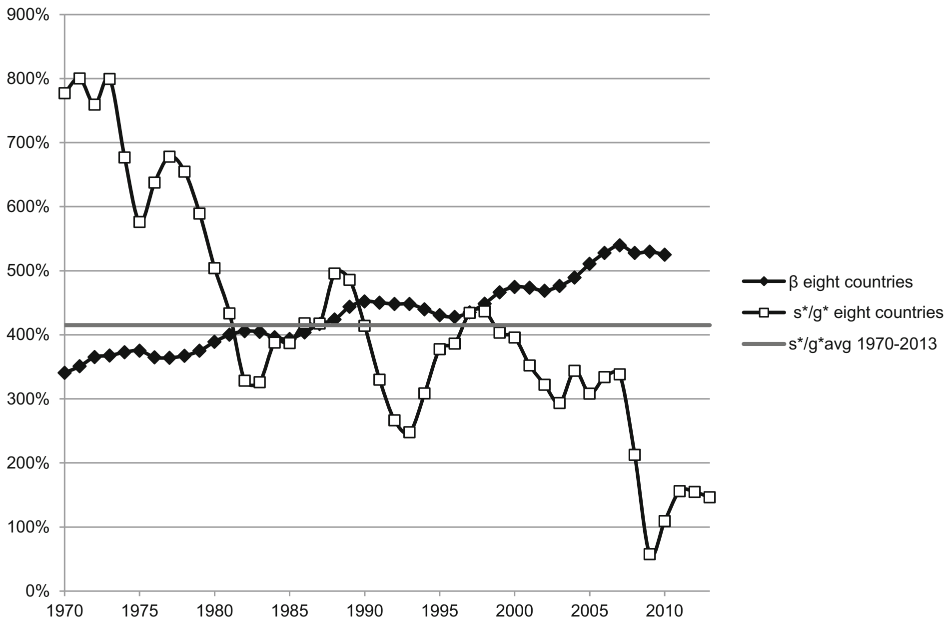

Figure 2. Wealth–income accumulation relative to growth in eight rich countries, 1970–2013. The eight countries are the United States, Japan, Germany, France, United Kingdom, Italy, Canada, and Australia. β is the capital/income ratio averaged for these eight countries over 1970–2010, based on the national income–national wealth annual data series in Table A1 of the online technical appendix accompanying Piketty and Zucman [2014], available at http://piketty.pse.ens.fr/en/capitalisback (Accessed 12 June 2014). The data for constructing the s^*/g^* ratio are based on the World Development Indicators [World Bank 2016]. The measure of s^* is gross national savings less the value of consumption of fixed capital and the value of net natural resource depletion as a percent of adjusted net national income (constant 2005 US$); the measure of g^* is average annual growth of net national income per capita adjusted for the value of net natural resource depletion (constant 2005 US$). Over 1970–2013, the average s^* for these eight countries was 6.9 percent, and g^* was 1.7 percent; consequently, the average s^*/g^* ratio for this period was 415 percent. The margin of error (95 percent confidence level) associated with the sample mean for s^* and g^* was 3.3 and 1.2, respectively. An online technical appendix that indicates the data for individual countries underlying the trends depicted in this figure is available at http://www.edwardbbarbier.com/Projects/Nature_Capital_and_Wealth_in_the_21st_Century/OTA.html.

415 percent over 1970–2013. Verifying this possible long-run trend will require more analysis of s_t^* and $s_t^*/\bar{g}^*$ in the coming years.

In comparison, very different trends in s_t^*, n_t^*, and $s_t^*/\bar{g}^*$ have occurred for low- and middle-income countries over the past few decades.

Figure 3 indicates the average annual rates of adjusted net saving s_t^* and natural capital depreciation n_t^* for a sample of 95 developing economies from 1979 to 2013. Both rates have varied considerably, and there were distinct periods when the adjusted net savings rate has fallen below and then risen above the rate of natural capital depreciation. For example, from 1979 until the mid-1980s, the rate of natural capital deprecation exceeded the rate of savings, whereas from the mid-1980s to the late 1990s the adjusted net savings rate rose and then remained largely above the rate of natural capital depreciation. But the savings rate also fell steadily to below 2 percent in 2000, whereas the natural capital depreciation rate begun rising from 4 to 5 percent in the 1990s to peak at 10 percent by the mid-2000s. However, since 2000, the adjusted net savings rate has also increased, and now exceeds the rate of natural capital depreciation, which has been hovering around 6–7 percent. On average from 1979 to 2013, both the rates of natural capital deprecation

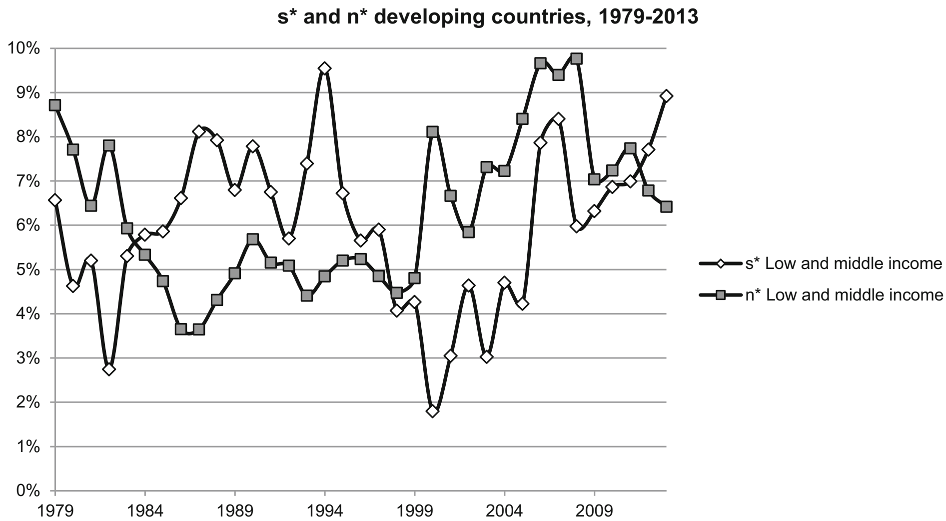

Figure 3. Adjusted net saving and natural capital depreciation in developing countries, 1979–2013, based on a sample of 95 low- and middle-income (or developing) countries, which are economies with 2013 per capita income of $12,735 or less. The data are based on the World Development Indicators (World Bank 2016). The measure of s^* is gross national savings less the value of consumption of fixed capital and the value of net natural resource depletion as a percent of adjusted net national income (constant 2005 US$); the measure of n^* is annual value of net natural resource depletion as a percent of adjusted net national income (constant 2005 US$). Over 1979–2013, the average s^* for the sample of developing countries was 6.0 percent, and average n^* was 6.3 percent. The margin of error (95 percent confidence level) associated with the sample mean for s^* and n^* was 2.1 and 1.8, respectively. An online technical appendix that indicates the data for individual countries underlying the trends depicted in this figure is available at http://www.edwardbbarbier.com/Projects/Nature_Capital_and_Wealth_in_the_21st_Century/OTA.html.

and adjusted net savings in developing countries were around 6 percent. These long-run averages, plus the converging trends in the two rates since 2000, indicate that, by and large, increases in other forms of capital are keeping pace with the large natural capital depreciation occurring in these economies. In addition, the rise in s_t^* since 2000 represents a significant increase in the annual rate of adjusted net wealth accumulation $\Delta W^*/Y_t^*$ for the sample of developing countries.

Because s_t^* has been rising for the 95 developing countries since 2000, the ratio $s_t^*/\bar{g}^*$ has generally increased, from 110 percent to over 500 percent of long-run growth (see Figure 4). This more recent trend in the $s_t^*/\bar{g}^*$ ratio seems to mirror a similar increase that occurred from the early 1980s to the mid-1990s. The average $s_t^*/\bar{g}^*$ of 350 percent over 1979–2013 for the 95 developing countries is still slightly lower than the average ratio of 415 percent over 1970–2013 for the eight rich economies (see Figure 2). However, it is premature to conclude whether the long-run average $s_t^*/\bar{g}^*$ ratio for the developing economies will start to rise, as it is not clear whether the current trend of accumulating more net wealth relative to increasing income with continue in subsequent years for this sample of developing countries.

To provide further insights into these contrasting trends for rich and developing countries, two robustness tests were performed. First, the group of eight high-income countries was extended to 27 high-income countries, all of which are members of the Organization of Economic Cooperation and Development (OECD). Second, the sample of 95 developing countries was divided into three subgroups: 23 low-income countries (per capita income $1045 or less), 37 lower middle-income countries (per capita income

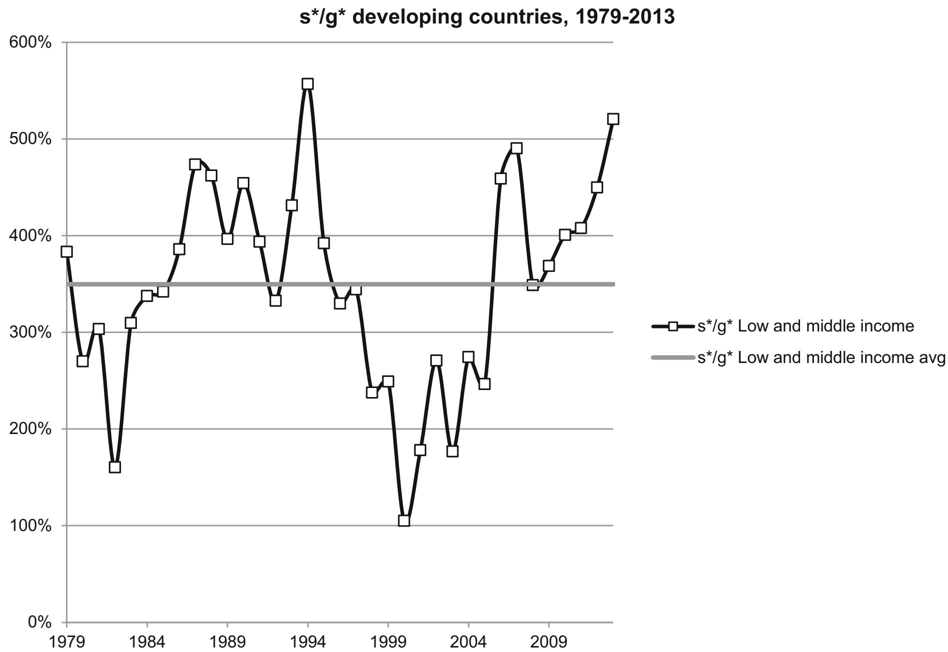

Figure 4. Wealth–income accumulation relative to growth in developing countries, 1979–2013, based on a sample of 95 low- and middle-income (or developing) countries, which are economies with 2013 per capita income of $12,735 or less. The data for constructing the s^*/g^* ratio are based on the World Development Indicators (World Bank 2016). The measure of s^* is gross national savings less the value of consumption of fixed capital and the value of net natural resource depletion as a percent of adjusted net national income (constant 2005 US$); the measure of g^* is average annual growth of net national income per capita adjusted for the value of net natural resource depletion (constant 2005 US$). Over 1979–2013, the average s^* for the sample of developing countries was 6.0 percent, and g^* was 1.7 percent; consequently, the average s^*/g^* ratio for this period was 350 percent. The margin of error (95 percent confidence level) associated with the sample mean for s^* and g^* was 2.1 and 0.5, respectively. An online technical appendix that indicates the data for individual countries underlying the trends depicted in this figure is available at http://www.edwardbbarbier.com/Projects/Nature_Capital_and_Wealth_in_the_21st_Century/OTA.html.

between $1046 and $4125), and 35 upper middle-income countries (per capita income between $4126 and $12,735).

The estimates for the 27 high-income countries produced almost identical trends for s_t^*, n_t^*, and $s_t^*/\bar{g}^*$ as depicted in Figures 1 and 2 for the sample of 8 high-income countries.[7] Thus, the findings that the adjusted rate of net national saving is converging to the rate of natural capital depreciation and that s_t^* has declined even faster than long-run growth over 1970–2013 appear to be highly robust across OECD high-income countries.

The estimates for the two middle-income subgroups also produced similar trends for s_t^*, n_t^*, and $s_t^*/\bar{g}^*$ as depicted in Figures 3 and 4 for the full sample of 95 developing countries, although the rate of adjusted net savings and long-run growth in adjusted net national income for upper middle countries were significantly higher.[8] However, for the low-income subgroup, n_t^* was approximately the same magnitude (6 percent) over 1979–2013 as for the full developing country sample, but s_t^* and $s_t^*/\bar{g}^*$ were consistently negative. These trends for the subsample of 23 low-income countries are portrayed in Figures 5 and 6.

As shown in Figure 5, the adjusted net savings rate across the 23 low-income economies has averaged −1.5 percent over 1979–2013, which was well below the

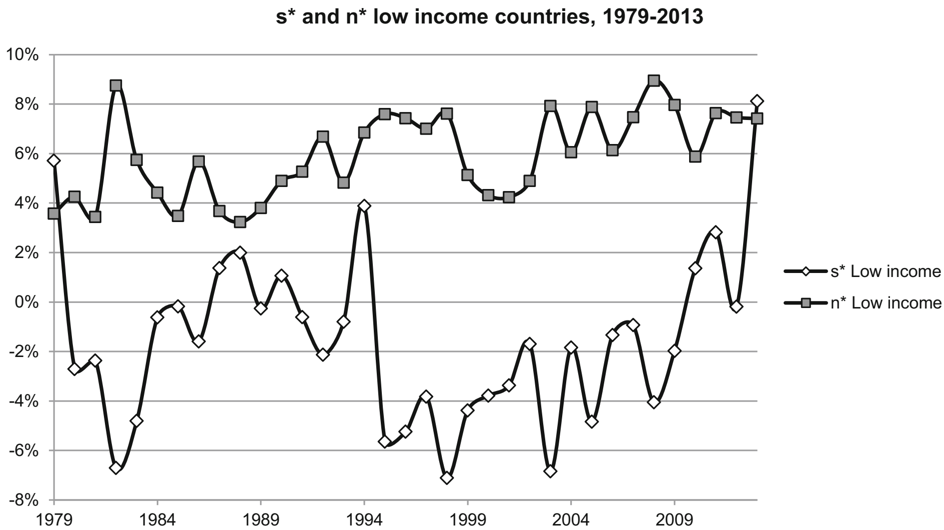

Figure 5. Adjusted net saving and natural capital depreciation in low-income countries, 1979–2013, based on a sample of 23 low-income countries, which are economies with 2013 per capita income of $1045 or less. The data are based on the World Development Indicators [World Bank 2016]. The measure of s^* is gross national savings less the value of consumption of fixed capital and the value of net natural resource depletion as a percent of adjusted net national income (constant 2005 US$); the measure of n^* is annual value of net natural resource depletion as a percent of adjusted net national income (constant 2005 US$). Over 1979–2013, the average s^* for the sample of low-income countries was −1.5 percent, and average n^* was 5.9 percent. The margin of error (95 percent confidence level) associated with the sample mean for s^* and n^* was 4.3 and 3.2, respectively. An online technical appendix that indicates the data for individual countries underlying the trends depicted in this figure is available at http://www.edwardbbarbier.com/Projects/Nature_Capital_and_Wealth_in_the_21st_Century/OTA.html.

average rate of natural capital depreciation of around 6 percent. However, as with the full sample of developing countries (see Figure 3), since 2000 the adjusted net savings rate for the low-income subsample has increased to converge with the rate of natural capital depreciation.

The trend in the $s_t^*/\bar{g}^*$ ratio for the 23 low-income economies appears to mirror the trend for the full sample of 95 developing countries (see Figures 4, 6). However, this ratio has been mainly negative, on average −435 percent, over 1979–2013 for the low-income subgroup. For these economies, adjusted net wealth accumulation fell on average each year at a rate that is four times more than the long-run growth. However, since 2000 the $s_t^*/\bar{g}^*$ ratio for the 23 low-income economies has been rising, and in the last few years has been significantly above zero. If this rising trend continues, then low-income countries could experience accumulation in net adjusted wealth at a faster pace than long-run per capita income growth.

CONCLUSION

Piketty [2014] and PZ have shown that the ratio of conventionally measured national wealth to national income has increased steadily over 1970 to 2010 for the eight richest economies – the United States, Japan, Germany, France, the United Kingdom, Italy, Canada, and Australia. This capital is predominantly private wealth, and it comprises largely financial and industrial capital and urban real estate (i.e., housing). In contrast, agricultural land is no longer a significant share of wealth in these economies.

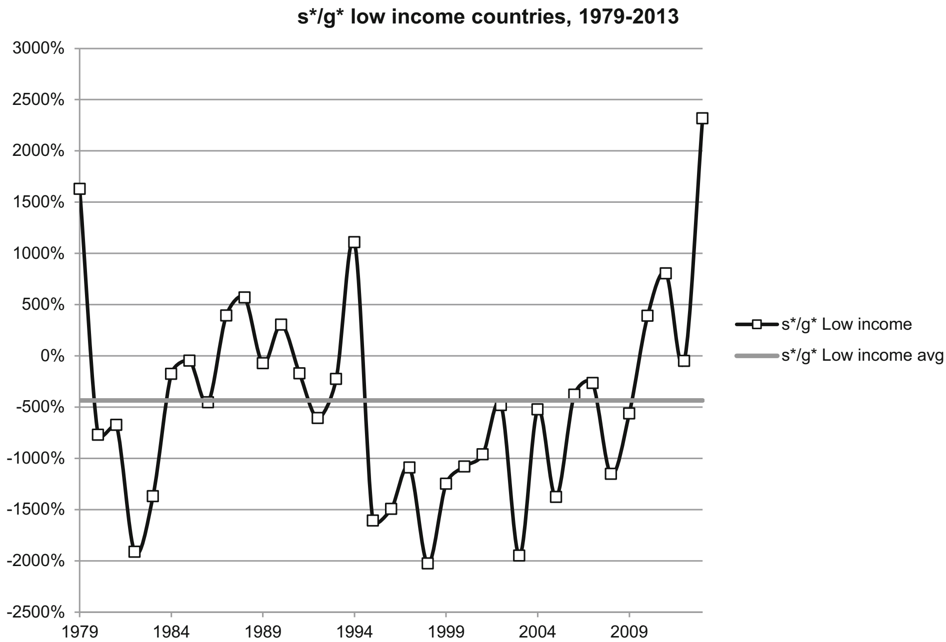

Figure 6. Wealth–income accumulation relative to growth in low-income countries, 1979–2013, based on a sample of 23 low-income countries, which are economies with 2013 per capita income of $1045 or less. The data for constructing the s^*/g^* ratio are based on the World Development Indicators (World Bank 2016). The measure of s^* is gross national savings less the value of consumption of fixed capital and the value of net natural resource depletion as a percent of adjusted net national income (constant 2005 US$); the measure of g^* is average annual growth of net national income per capita adjusted for the value of net natural resource depletion (constant 2005 US$). Over 1979–2013, the average s^* for the sample of low-income countries was −1.5 percent, and g^* was 0.4 percent; consequently, the average s^*/g^* ratio for this period was −435 percent. The margin of error (95 percent confidence level) associated with the sample mean for s^* and g^* was 4.3 and 1.0, respectively. An online technical appendix that indicates the data for individual countries underlying the trends depicted in this figure is available at http://www.edwardbbarbier.com/Projects/Nature_Capital_and_Wealth_in_the_21st_Century/OTA.html.

This paper has demonstrated how these trends in wealth–income ratios for the eight economies over the past four decades are influenced by the depreciation of key natural resources essential to domestic production, such as fossil fuels, minerals, and forests. Although there may have been substantial accumulation of wealth relative to income, natural capital depreciation in these economies is being compensated less and less each year by net increases in other forms of capital. This implies that wealth accumulation, net of natural capital depreciation, has declined as a share of national income. In comparison, in low- and middle-income countries, net increases in other forms of capital have largely kept pace with the high rate of natural capital depreciation, and in recent years these countries accumulated more net wealth relative to income growth.

These trends have several important implications. For the eight high-income countries, the long-run convergence of adjusted net savings rates with natural capital depreciation rates should raise concerns about overall wealth creation in these economies. For these countries, policies to encourage more economy-wide investment in other forms of capital to raise adjusted net savings rates, and especially the long-run rate of net wealth accumulation relative to growth, are urgently needed. Although human capital accumulation is not included in the analysis of this paper, there is also concern that investments in skills, training, and education in these economies are lagging in these economies, both absolutely and relative to natural resource use [Barbier 2015; Goldin and Katz 2008; OECD 2011]. For developing countries, although net wealth accumulation appears to have kept pace with income growth in recent years, the high rate of natural capital depreciation remains a concern. Over the long run, the current rate of around 7 percent across all low- and middle-income countries may adversely affect the sustainability of their development efforts. A key focus of policies should be to improve the efficiency and sustainability of natural resource use so that natural capital depreciation in developing countries eventually converges to the long-run rate of 1–2 percent of high-income economies. This could be especially important for low-income countries, where reducing natural capital depreciation may prove instrumental to improving the adjusted net wealth–income ratio of these poorer economies over the long run.

Verifying the long-run trends in net national savings, income, and income growth adjusted for natural capital depreciation identified in this paper will require long-term data on natural capital stocks as well as depreciation rates.[9] As we develop better measures of natural capital stocks and depreciation for 70–100 years or even longer, other considerations need to be taken into account, such as the role of demographic transitions, total factor productivity changes, appropriate accounting for long-run natural capital asset and price appreciation, and the economic contributions of ecosystems and other environmental assets beyond fossil fuels, minerals, and forests [Arrow et al. 2012; Fenichel and Abbott 2014; Greasley et al. 2014]. For example, Fenichel and Abbott [2014] develop a capital-theoretic approach to estimating the accounting prices and stock changes that is applicable to a wide range of natural resources and ecosystem services, which they use to estimate the natural capital value over 1985–2005 for the Gulf of Mexico reef fish stock. Greasley et al. [2014] show that, for Great Britain, the net national saving rate adjusted for human and natural capital changes from 1765 to 2010 is substantially influenced by the changes in total factor productivity that have occurred since 1765. Such improvements in the long-run measurement of natural capital for a wide range of economies are essential, but in the meantime, extending the PZ approach to account for natural capital depreciation can still yield important insights into the rate of adjusted net wealth accumulation each year relative to income and growth. As such estimates have implications for long-run levels of the adjusted net wealth–income ratio of economies, the methods and indicators developed in this paper should be incorporated with current efforts to include natural wealth adjusted net savings in national accounts [Arrow et al. 2012; UNU-IHDP-UNEP 2014; World Bank 2011, 2016].

Finally, the main purpose of this paper is to show how net depreciation in an economy's stock of fossil fuels, minerals, and forests – the economy's natural "capital" or "wealth" – affects net national savings adjusted for such natural wealth depreciation and the ratio of this saving rate with respect to long-run growth. However, depletion and use of these natural resources also contributes to considerable environmental externalities, including pollution that affects the welfare of individuals in an economy and carbon emissions that may lead to welfare losses globally through inducing climate change. Extending the methodology of this paper to include these additional externalities associated with natural resource depletion will be an important step for future research, especially in the case of low- and middle-income economies. If the rate of natural capital depreciation for developing economies continues to rise, as appears to be the general trend since 2000 (see Figure 3), the environmental externalities accompanying this depreciation are also likely to increase as a share of adjusted net national income.

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APPENDIX

PZ's one-good model wealth accumulation model can be extended by adapting the approach to accounting for natural capital depreciation in an intertemporal optimizing behavior model [Hamilton and Clemens 1999; Hartwick 1990; Solow 1986], which was originally developed by Weitzman [1976].

To expedite the analysis, assume that the economy is closed and has no net foreign income. Let K_t be the domestic capital stock of the economy at time t and N_t its endowment of available natural resources for production. Y_t is the net national income (i.e., national income less domestic capital depreciation) at time t, C_t is the aggregate consumption, and S_{gt} is the gross national savings flow between time t and $t + 1$. Ignoring any price effects, gross national savings is defined as $S_{gt} = (K_{t+1} - K_t) + \delta K_t$, where δK_t is the domestic capital depreciation in time t. Aggregate national income is produced by employing capital, labor L_t , and a flow of input R_t extracted from the natural resource endowment, and corresponds to the identity $F(K_t, L_t, R_t) = C_t + S_{gt}$. Finally, the change in the natural resource stock between time t and $t + 1$ is determined by $N_{t+1} - N_t = G(N_t) - R_t$, where $G(N_t)$ represents the natural growth rate for any renewable resources (but can either be assumed zero for exhaustible resources, or be additions to stocks through exploration or discovery G_t).

If social welfare in time t is represented by the utility function $U(C_t)$, then the current-value Hamiltonian for social-welfare maximization is

$$H = U(C_t) + \lambda_t[K_{t+1} - K_t] + \mu_t[N_{t+1} - N_t],$$

where λ_t and μ_t are the shadow values of capital and natural resources, respectively. Linearizing the utility function, so that $U(C_t) = U_C C_t$, and using the first-order conditions $U_C = \lambda_t$ and $\lambda_t F_R = \mu_t$, the current-value Hamiltonian can be rewritten as

$$\frac{H}{U_C} = C_t + [K_{t+1} - K_t] + F_R[G(N_t) - R_t] = C_t + S_{gt} - \delta K_t + F_R[G(N_t) - R_t].$$

The last term is the net deprecation of natural resources used in production. If this term is negative, it represents the value of the amount of the resource endowment that is "used up" to produce national income in time t.

In the above expression, $C_t + S_{gt} - \delta K_t = Y_t$ is the net national income as defined by PZ. It follows that net national income adjusted for natural capital depreciation, or *adjusted net national income*, is $Y_t^* = Y_t - F_R[G(N_t) - R_t]$. Similarly, as PZ's net national saving is $S_t = Y_t - C_t = S_{gt} - \delta K_t$, then the adjustment to this saving for natural capital depreciation, or *adjusted net savings*, is

$$S_t^* = S_t + F_R[G(N_t) - R_t] = [K_{t+1} - K_t] + \mu_t[N_{t+1} - N_t].$$

Following PZ's example of equating domestic capital with the market value of national wealth W_t at time t, and denoting the market value of the resource endowment as $\tilde{N}_t$, then the adjusted net national savings can be defined as

$$S_t^* = [W_{t+1} - W_t] + \left[\tilde{N}_{t+1} - \tilde{N}_t\right] = W_{t+1}^* - W_t^*, \quad \text{where} \quad \tilde{N}_t \approx \mu \tilde{N}_t \text{ and } \tilde{N}_{t+1} \approx \mu \tilde{N}_{t+1}.$$

As shown by Dasgupta [2001], Ferreira et al. [2008], Greasley et al. [2014], and Hamilton and Hartwick [2005], cross-country wealth comparisons should account for the reductions in per capita wealth due to population growth. This effect can be accommodated easily in the above framework. Let population grow at rate η_t such that $L_{t+1} = (1+\eta_t)L_t$. Using a "hat" (^) to denote a per capita variable, $\hat{K}_{t+1} - \hat{K}_t = \hat{S}_{gt} - \delta \hat{K}_t - \eta_t \hat{K}_{t+1}$ and $\hat{N}_{t+1} - \hat{N}_t = g(\hat{N}_t) - \hat{R}_t - \eta_t \hat{N}_{t+1}$, where $g(\hat{N}_t) = G(N_t/L_t)$. Consequently, adjusted net savings per capita is

$$\hat{S}_t^* = \hat{S}_t + f_{\hat{R}}\left[g(\hat{N}_t) - \hat{R}_t\right] = \left[\hat{K}_{t+1} - \hat{K}_t\right] + \mu_t\left[\hat{N}_{t+1} - \hat{N}_t\right] + \eta_t\left[\hat{K}_{t+1} + \mu_t \hat{N}_{t+1}\right],$$

where $\hat{S}_t = \hat{S}_{gt} - \delta \hat{K}_t f(\hat{K}_t, \hat{R}_t) = F(K_t/L_t, R_t/L_t, 1)$, $U(C_t/L_t) = u(\hat{C}_t) = u_{\hat{C}}\hat{C}_t$, and the relevant first-order conditions are now $u_{\hat{C}} = \lambda_t$ and $\lambda_t f_{\hat{R}} = \mu_t$.
Adjusted net national savings per capita is therefore

$$\hat{S}_t^* = \left[\hat{W}_{t+1} - \hat{W}_t\right] + \left[\hat{\tilde{N}}_{t+1} - \hat{\tilde{N}}_t\right] + \eta_t\left[\hat{W}_{t+1} + \hat{\tilde{N}}_{t+1}\right] = (1+\eta_t)\hat{W}_{t+1}^* - \hat{W}_t^* = \Delta \hat{W}^*.$$

The additional term $\eta_t \hat{W}_{t+1}^*$ represents the increased savings per capita that is required to overcome the reduction in per capita wealth due to population growth. This is similar to the result derived by Ferreira et al. [2008] using the model developed by Hamilton and Hartwick [2005].

Given that the adjusted net savings rate is by definition $s_t^* = S_t^*/Y_t^* = \hat{S}_t^*/\hat{Y}_t^*$, then it follows that $s_t^* = \frac{\Delta W^*}{Y_t^*} = \frac{\Delta \hat{W}^*}{\hat{Y}_t^*}$. The adjusted net savings rate is also an indicator of the annual change in adjusted net wealth per capita relative to adjusted net national income per capita.

Notes

1. Thus, both PZ and Piketty [2014] also refer to "national wealth" as "national capital."
2. As PZ point out, in a one-good model of wealth accumulation, and more generally in a model with a constant relative price between capital and consumption goods, there are no capital gains or losses.
3. As shown in the appendix, the adjusted net savings rate is also an indicator of the annual change in adjusted net wealth per capita relative to adjusted net national income per capita $s_t^* = \frac{\Delta \hat{W}^*}{\hat{Y}_t^*}$, where η_t represents the population growth and a "hat" (^) indicates a per capita variable.
4. Jones [2015] and Krussell and Smith [2015] note that the steady-state relationship $\beta = s/g$ employed by PZ and Piketty [2014] is mathematically equivalent to the more familiar steady-state capital–income ratio condition in the Solow–Swan model $\beta = K/Y_g = s_g/(g_g + \delta)$, where s_g is the gross savings rate, Y_g is the gross national income, and g_g is the balanced growth rate. However, Krussell and Smith [2015] maintain that assuming a constant net savings rate is more problematic theoretically and empirically than the assumption of a constant gross savings rate s_g in the conventional Solow–Swan balanced growth equilibrium. In contrast, the one-good wealth accumulation model developed here assumes intertemporal optimizing behavior rather than a constant (either net or gross) savings rate, and conditions (1) and (2) do not require imposing a balanced growth equilibrium.
5. Further details on this methodology can be found in World Bank [2011] and in the notes accompanying World Bank [2016]. Although the depreciation of key natural resources, such as fisheries and freshwater supplies, is missing from this measure, the net depletion of subsoil assets and forests by economies accounts for much of their natural capital used up in current production and wealth accumulation.
6. However, Jones [2015] shows that, when the value of the capital stock for the United States, France, and the United Kingdom calculated by PZ and Piketty [2014] excludes land and housing, the rise in the capital–

output ratios for each of these three countries in recent decades is more gradual. For example, in France, "the rise in the capital–output ratio since 1950 is to a great extent due to housing, which rises from 85 percent of national income in 1950 to 371 percent in 2010" [Jones 2015, p. 41].

7. The 27 high-income countries in this sample are Australia, Austria, Belgium Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Japan, Korea Republic, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, the United Kingdom, and the United States. High-income economies are those in which 2013 GNI per capita was $12,736 or more. Over 1970–2013, the average s^* for these 27 countries was 9.5 percent (± 3.0), n^* was 1.3 percent (± 1.0), g^* was 2.0 percent (± 1.2), and the s^*/g^* ratio was 462 percent. An online technical appendix that depicts the corresponding figures for this sample and the underlying data for individual countries is available at http://www.edwardbbarbier.com/Projects/Nature_Capital_and_Wealth_in_the_21st_Century/OTA.html.
8. Over 1970–2013, the average s^* for lower middle-income countries was 6.7 percent (± 3.3), n^* was 6.0 percent (± 1.9), g^* was 1.7 percent (± 1.2), and the s^*/g^* ratio was 386 percent. Over 1970–2013, the average s^* for upper middle-income countries was 9.5 percent (± 3.2), n^* was 6.9 percent (± 3.9), g^* was 2.6 percent (± 0.9), and the s^*/g^* ratio was 369 percent. An online technical appendix that depicts the corresponding figures for these two subgroup samples and the underlying data for individual countries is available at http://www.edwardbbarbier.com/Projects/Nature_Capital_and_Wealth_in_the_21st_Century/OTA.html.
9. For example, PZ are able to estimate the (conventional) wealth–income ratio β for considerable periods of time; e.g., since 1810 for the United Kingdom, France, and the United States, since 1860 for Germany, since 1960 for Australia, and since 1970 for Canada, Italy and Japan. In contrast, the World Bank [2011] has estimated the total wealth of 124 countries, including natural capital, for three years (1995, 2000, and 2005). The only long-run historical measure of adjusted net savings, roughly equivalent to s^* in this paper, has been estimated by Greasley et al. [2014] for Great Britain over the period 1765–2000.

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