Testing Genuine Savings as a forward-looking indicator of future well-being over the (very) long-run.

Abstract:

Genuine Savings (GS) has been much used in recent years as an indicator of a country's sustainability. According to some theorists (e.g. Arrow et al, 2012), under certain conditions a country with a positive level of GS should experience non-declining future utility, given the assumption of unlimited substitutability among all forms of capital (sometimes called "weak" sustainability). This paper reports the first very long-run tests of GS (also called comprehensive investment or adjusted net savings) as a forward-looking indicator of future well-being. We assemble data for British capital back to 1765, and construct several net investment measures which are used as indicators of two alternative measures of future well-being: consumption per capita and real wages. An allowance for a "value of time" due to exogenous technological progress is included in some GS measures, and we demonstrate the importance of this measure and the choice of discount rate over the very long-run. On the whole, our results do not reject the postulated relationship between GS and future well-being, and show GS can be a forward looking indicator of future well-being for periods of up to 100 years.

Keywords: sustainable development, genuine savings, comprehensive investment, future well-being, British economic history, technological progress.

1. Introduction: Genuine Savings as an indicator of sustainable development

The idea of using a nation's Genuine Savings (also referred to as Comprehensive Investment, Inclusive Investment and Adjusted Net Savings) as a forward-looking indicator of "weak" sustainability is now well-known [1-6]. Pearce and Atkinson [7] were the first to suggest that the change over time in a country's capital stocks was an indicator of the sustainability of its development path. This relies on the assumption that all forms of capital – produced, natural, human and social capital - can be aggregated in monetary units and are perfectly substitutable for each other in terms of maintaining well-being over time. These theoretical postulates underpin theories of "weak" sustainability, as opposed to theories of "strong" sustainability that deny the possibility of either aggregating monetized values for all capital, and/or the possibility of their unlimited substitution. Genuine Savings (GS) estimates have been reported for virtually of all the world's economies, typically using World Bank datasets [e.g. 3, 8] for years after 1970, and longer time series of GS for individual countries have also become available [9].

In this paper, we investigate the relationship between increasingly-comprehensive measures of GS and two well-being indicators for Great Britain over the period 1765-2000. We test a set of hypotheses which relate GS to changes in future well-being, using the framework suggested by Ferreira, Hamilton and Vincent [10], and investigate whether well-being and GS measures are cointegrated over time to improve the power of our hypothesis testing. In doing so, we also provide a test of an important general result in neoclassical growth theory originally associated with Weitzman [11]. Our paper considerably extends the scope of the existing literature by considering patterns of GS and well-being over a very long-time period for a single country: existing empirical tests rely on very-much shorter-run panels.

Sustainable development has been defined by Arrow et al [5] as an economic path along which intergenerational well-being does not decline over time. Well-being at time *t* is defined as the present value of discounted utility from consumption (measured in monetary terms) over the accounting period, assuming a constant discount rate. This requires that "comprehensive wealth"- the value of the economy's assets - be non-declining over the same period. Arrow et al then define comprehensive investment as the change in comprehensive wealth at time *t*, and claim that intergenerational well-being is rising if comprehensive investment – Genuine Savings, in the terminology of paragraph one above – is positive when evaluated at the correct shadow prices. Pezzey [12] defined sustainability differently to Arrow et al (2012), and argued that GS is a one-sided indicator only, in that a negative value of GS at time *t* leads to falling well-being over time (in his model, well-being is an economy's per-person utility), but no equivalent statement can be made for a positive level of GS and non-declining well-being. Pezzey [12] also noted that this one-sided predictive ability of GS only holds in present value maximising (optimal) economies with a constant discount rate.[1] Finally, the GS indicator can be adjusted to deal with exogenous changes in the production possibilities of an economy (exogenous technological change, for instance) and/or changes in population which must be addressed for the link with future well-being to hold [12]. Despite their differences, the work of both Arrow et al, and Pezzey, provide a strong motivation for the empirical testing of GS as an indicator of sustainability over the long-run.

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[1] Pezzey [12] also shows that a declining value of Green Net National Product implies falling future utility in this optimal economy.

The relationship between a country's asset base, annual changes in this asset base and future well-being is also a feature of neo-classical growth theory. Weitzman [11] showed that in an economy producing a single consumption good from a capital stock which comprises natural as well as produced capital, and that is proceeding along a path which maximises the present value of consumption from time zero to infinity at a constant discount rate *r,* net national product is given by the Hamiltonian of the associated constrained optimisation problem.[2] As Ferreira and Vincent [2] pointed out, this result implies that average future consumption will be greater than current consumption if GS (which they call net investment) is positive and net investments in all forms of capital are measured using the correct shadow prices (although this does not rule out consumption levels falling between some periods). The Weitzman result also implies that the relationship between GS and changes in future consumption can be used to test whether an economy is following an optimal development path [13].[3] In the next two sections, we review the empirical testing framework to be used in this paper, and show how it relates to the underlying theory.

1.1. Testing Genuine Savings: a framework, and previous results

In this paper, we make use of the theoretical and empirical testing framework set out in Ferreira, Hamilton and Vincent [10] (FHV, hereafter). Starting from the model of Hamilton and Hartwick [14], FHV showed, with a constant population growth rate of γ, a population at

[2] Ferreira and Vincent [2] note that this constant discount rate is a reasonable assumption given their data on world economic development over the period 1970-2001.

[3] We thank Jack Pezzey for pointing this out to us.

time t of N, a consumption discount rate of ρ[4], and year-on-year change in produced capital K denoted $\dot{K}$, that per capita genuine savings g is given by:

$$g = \frac{\dot{K}}{N} - F_R\ r - \gamma\omega \qquad (1)$$

where $(F_R\ r)$ is the shadow value of per capita natural capital extraction (e.g. fossil fuel extraction) and ω is per capita wealth, which is the sum of per capita natural and produced capital stocks W at time t divided by the population N. This shows GS is determined by per capita net change in produced and natural capital (the first two terms on the right-hand side of equation 1) adjusted by a "wealth dilution effect" from population growth $-\gamma\omega$. The key theoretical relationship derived by FHV is that in any period t, the value of g is equal to the discounted value of changes in per capita consumption from t to infinity if the consumption discount rate ρ is adjusted downwards by the (constant) population growth rate [15].

If population grows at a varying rate, then the relationship between per capita GS and the present value of changes in future consumption is altered. FHV expressed this new relationship in discrete time as follows:

$$\sum_{v=t+1}^{t+T} \frac{\left(\frac{C_{iv+1}}{N_{iv+1}} - C_{iv}/N_{iv}\right) + (\gamma_{iv+1} - \gamma_{iv})(W_{iv}/N_{iv})}{\prod_{j=t+1}^{v}(1+\rho_{ij} - \gamma_{ij})} = g_{it} \qquad (2)$$

where for country i, W represents total (produced plus natural) capital, t is time, and all the other terms are as described above. W can be extended to include other forms of capital, such as human or social capital. Equation (2) states that, in a competitive economy,[5] the per capita rate of genuine saving for country i at time t should be equal to the present value of

[4] Note that we therefore use a constant discount rate (one that does not vary over time) in our empirical procedures.
[5] Note that Hamilton and Hartwck [14] also assume that all externalities are internalised, which is clearly not borne out in reality.

future changes in per capita consumption adjusted for a term which shows the effects of population growth on per capita wealth – the wealth dilution effect with non-constant population growth rates. FHV then derived from (2) two equations which can be estimated to test if (2) holds. With varying population growth rates, the equation to be estimated is:

$$PV\Delta C_{it} + PV(\Delta\gamma_{it}\omega_{it}) = \beta_0 + \beta_1 g_{it} + \epsilon_{it} \quad (3)$$

If population grows at a constant rate over time, then (3) simplifies to:

$$PV\Delta C_{it} = \beta_0 + \beta_1 g_{it} + \epsilon_{it} \quad (4)$$

For both (3) and (4), the strictest test of the theoretical prediction shown by (2) is that $\beta_0 = 0$ and $\beta_1 = 1$ jointly.

Ferreira and Vincent [2] was the first paper to test empirically whether GS is indeed a forward looking indicator of sustainability defined as achieving rising average well-being over time, using the general framework set out above.[6] As they observed, "...the reliability of empirical estimates of comprehensive net investment as [a] sustainability indicator has gone unexamined". Their paper used World Bank data from 1970 – 2001 for 93 countries, although the need to calculate the difference between average future and current consumption means that they tested a version of (4) only over the period 1970-1991. Ferreira and Vincent proposed four alternative measures of net changes in a country's assets; gross investment in produced capital; net investment in produced capital; net investment adjusted for depletion of natural capital (green net savings), and finally green net savings augmented by investment in education, which they termed Genuine Savings.

[6] Although they use the difference between average future consumption and current-period consumption as the left-hand side variable, rather than the present value of changes in future consumption.

They then tested three hypotheses relevant to this paper which represent increasingly-strict interpretations of the underlying theory noted above:

H*: $\beta_0 = 0$ and $\beta_1 = 1$

H**: $\beta_1 > 0$ and $\rightarrow 1$ as the net investment term includes more types of capital (that is, as the measure of year-on-year changes in total capital is more-comprehensive).

H***: $\beta_1 > 0$.

Their results showed that H* is rejected for all definitions of net investment. For H**, they found that β_1 is always positive, and that its absolute value increases as more comprehensive measures of the capital stock are used, although it falls when education spending is included. The authors speculated that this reflects the extent to which current education spending is a poor measure of changes in the stock of human capital. H*** is not rejected. Changing the time period over which present values are calculated to 20 years rather than 10 years results in higher values for β_1.

World Bank [3] examined the empirical support for GS theory using OLS regressions across a number of countries for 5 consecutive 20-year periods using data from 1976-2000, but found rather mixed signals because of the number of "false positive" and "false negative" predictions of changes in future consumption which can be made using estimates of net investment. For both gross saving and genuine saving, they found that they cannot reject $\beta_1 = 1$, concluding that "…Genuine Savings is a good predictor of changes in future welfare as measured by consumption per capita" (p. 82).

Finally, FHV [10] used (3) and (4) above to test the relationship between the present value of changes in future consumption and genuine savings. They employed a World Bank data set of 64 developing countries over the period 1970-2003, which implies an estimation period of 1970-1982 to measure discounted changes in future consumption over a 20 year period. As in Ferreira and Vincent [2], this study used increasingly-comprehensive measures of changes in a country's assets: gross savings, net savings (i.e. net investment in produced capital), green savings (net savings minus depreciation of elements of natural capital) and population-adjusted savings (green savings adjusted by the wealth dilution term). This allowance for the wealth dilution effect is the main conceptual change over Ferreira and Vincent [2]. They tested the joint hypothesis that $\beta_0 = 0$ and $\beta_1 = 1$; and a weaker hypothesis that $\beta_1 > 0$. Their most "striking result" is that the hypothesis $\beta_1 > 0$ is supported only for green savings and its population-adjusted equivalent. However, the estimates of β_1 remain "significantly below 1" in all four models. They also concluded that there was a "lack of significant impact for the adjustment for wealth dilution" (p.246).

1.2 Testing Genuine Savings in the (very) long-run

There is thus rather limited evidence on the link between GS and future well-being. In this paper we aim to extend FHV in a number of important ways. First, we assemble and then use a data set which extends over a much longer time period, at around 250 years. We test whether the implications of theory concerning the relationship between GS and future well-being are borne out in this long run data. Given that sustainable development is a long-term policy concern, and that the theoretical models behind the GS indicator are cast in infinite time, this seems an important and novel advantage. Second, we investigate the effects of allowing for a "value of time passing"; treating time as an uncontrolled capital stock that through exogenous technological progress expands the economy's production possibilities

[16]. Such technological change is, as we will see, an issue that becomes pressing over longer time-frames. Third, we include changes in human capital, measured through investments in education. World Bank [3] note that the process of development can be characterised as countries converting natural capital into other forms of capital including human capital, whilst Arrow et al [5] also acknowledge the importance of investments in human capital. Finally, we test two alternative indicators of future well-being: changes in the present value of consumption, as per FHV; and changes in the present value of real wages. Hypotheses tests are accompanied by tests for cointegrating relationships to show the robustness of results.

Based on (3) and (4) above, the main hypotheses tests relate to the theoretical relationship between GS and future well-being:

$$PV\Delta C_{it} = \beta_0 + \beta_1 {g^*}_{it} + \epsilon_{it} \qquad (5)$$

where all terms are as in (4) except that ${g^*}_{it}$ can now include both changes in human capital and the value of technological progress as part of the stock of capital, as well as changes in produced and natural capital. If we allow for non-constant population growth rates and a wealth-dilution effect then the relevant theoretical relationship is:

$$PV\Delta C_{it} + PV(\Delta\gamma_{it}\omega_{it}) = \beta_0 + \beta_1 {g^*}_{it} + \epsilon_{it} \qquad (6)$$

Based on (5) and (6), the hypotheses to be tested are then:

H1: $\beta_0 = 0$ and $\beta_1 = 1$ jointly

H2: $\beta_0 = 0$ and/or $\beta_1 = 1$ independently

We conduct these tests over three different forward-looking periods, which are t+20, t+ 50 and t+100. The hypotheses tests are conducted for an increasingly-comprehensive set of measures of the capital stock. The hypotheses tests for our core results are based on (5), but with *i*=1 (since our data is for one country only). One of the sensitivity analyses includes the wealth-dilution effect, and is thus based on (6). We also examine the effects of using changes in future real wages rather than changes in future consumption as the indicator of future well-being; the effects of changing the discount rate used in the calculation of present values; and the effects of changing the data period over which we conduct the hypotheses tests based on (5). In what follows, section 2 sets out the data on which our hypothesis testing is based. Section 3 presents our core results and the sensitivity analyses for the two alternative well-being indicators. Section 4 concludes, and offers some directions for future work.

2. Data

Our data relate to Great Britain, and descriptive statistics for the key variables are reported in the Data Appendix. As some historical and modern data pertains to the entirety of the United Kingdom at any given time, for some series this necessitates an adjustment for the exclusion of the whole of Ireland before 1921, and Northern Ireland thereafter. The economic and environmental history of Ireland is sufficiently distinct from that of Great Britain to warrant this procedure, and also ensures that we are dealing with a consistent geographical unit over time.

Of course, the quality of the data both for the distant past and more recent years is crucial to the reliability of our tests. The historical data constructions draw upon a long tradition of scholarship in quantitative economic history, for a survey see Greasley and Oxley [76]. For the British economy especially, the quantitative-historical record running back to the eighteenth century is of a remarkably high standard for most of the variables needed for the series 1-5 below. Thus, in areas which have been subject to extensive scrutiny by historians, for example national accounts including investment, wages and prices, and the coal industry, we have been able to draw upon reliable estimates. In particular, we have made extensive use of Charles Feinstein's highly regarded research which set out historical produced-investment series, constructed to mesh with contemporary data. Some areas have received less attention from quantitative historians, for example estimates for elements of natural and also of human capital. Further historical research in these areas would be valuable

In this study we have largely used data series widely-accepted by economic historians. We have indicated below where data are less certain and discuss how the data quality might affect the results. Historians' reconstructions have been linked to Office of National Statistics (ONS) estimates, utilizing consistent definitions. Feinstein's [17] important estimates of historical national income, output and expenditures for the years 1855-1965 were defined to splice with modern CSO/ONS estimates, and his investment data for earlier years follow the same procedures. Fuller [75] assessed the quality of Feinstein's data and highlighted their value for gauging changes over time. Inevitably, the reliability of the historical data, especially for years before 1855 is less than for contemporary ONS estimates, although we would venture that the quality of British historical data stands favourably in comparison to World Bank estimates of some African and Asian countries. Fuller details of the data sources are in the Data Appendix and McLaughlin *et al* [18].

To conduct the hypotheses tests H1 and H2, a series of increasingly-comprehensive measures of investment are constructed:

1. NETPINV: annual changes in net produced capital and net overseas assets

2. GREENINV: NETPINV plus changes in elements of the stock of natural capital

3. GS: GREENINV plus changes in human capital

4. GREENTFP and GSTFP: GREENINV and GS plus the value of changes in exogenous technological progress

5. GSWPOP and GSTFPWPOP: GS and GSTFP less wealth dilution per capita

2.1 NETPINV, net domestic investment and net overseas assets

Produced investment comprises net domestic fixed capital formation, changes in inventories and net foreign investment. These data are from Feinstein & Pollard [19], Feinstein [17] and ONS publications. Table 1 shows the nominal values of the series relative to nominal GDP. Feinstein's GDP data as reported in Measuring Worth [20] are utilized here. They use a variety of balancing procedures for combining income, output and expenditure estimates, see Officer [21]. Measuring Worth's GDP estimates are spliced with those of Broadberry et al [22] in 1870. The latter is an output-based series for Great Britain. Since our post 1870 data are scaled for the exclusion of Ireland, the Broadberry et al estimate of British GDP in 1870 is adopted as the level benchmark in the splicing.

Table 1 near here

The average value of net produced investment relative to GDP was nearly twice as high 1860-1914, compared the preceding century 1760-1860. This was largely due to higher net overseas investment. Produced investment fell dramatically during the world wars, and the investment ratio was low between 1914 and 1945. The recovery of produced investment after 1945 was largely due to a rise in domestic fixed capital formation.

2.2 GREENINV: NETPINV plus changes in the stock of natural capital

Our measure of green investment includes changes in the forestry stock and the extraction of coal, oil, natural gas, iron ore, lead, copper, tin, and zinc.[7] Shadow prices for each capital stock change are ideally calculated by subtracting the marginal cost from the price to correspond to the theoretical model from which the GS indicator is derived. In practice, we make use of market prices and, typically, average rather than marginal costs. This means that our numerical estimate of GS does not correspond exactly to its theoretical equivalent – as is true for all World Bank estimates.

As direct data on the area or stocking rate of all British woodland was not collected until well into the twentieth century, our estimates must proceed from fragmentary information and research by landscape and environmental historians. The area of British woodland rose from around 1 million hectares in 1765 to around 3 million in 2000, augmenting the stock of natural capital. This shift is well-established and it is clear that nearly all of the change

[7] Full data sources are outlined in the appendix and McLaughlin *et al* [18].

occurred during the twentieth century, and before 1900 the stocking rate of woodlands was both low and changed little, with a nadir of the standing volume around 1871. Despite substantial felling during the world wars, standing volume rose during the twentieth century, most markedly after 1945. Thus despite the paucity of direct data, our estimates can be considered reliable, and augmentation or diminishing of natural capital through change in the stock of timber was vanishingly small before 1900. Moreover, the increase in the rental value of woodlands has been low relative to produced investment or GDP. A variety of timber prices are used to estimate the price per cubic metre (see the Data Appendix) and combined with felling costs, essentially the cost of labour per cubic metre felled, to gauge changes in the value of standing volumes. The sharpest rise in the rental values of woodland occurred in the period after 1946 and averaged 0.18% of GDP, whereas the deepest decline occurred 1914-18, when around one-third of the forest stock was felled, and the fall in rental value averaged -0.18% of GDP.

The British economy extracted substantial quantities of non-renewable mineral resources over the last 250 years, and the issue has received a commensurate amount of attention from historians. Trends in extraction and costs of coal are well-known. Coal mining dominated mineral extraction until the 1970s, and oil and gas thereafter. Extracted coal rents are measured by the difference between pithead coal prices and labour costs per tonne, multiplied by coal production, using the sources described in the Data Appendix. In the case of oil and gas marginal extraction costs are near zero, and the value of production is used to measure the value of extracted rents. While production estimates for iron ore, copper, tin, zinc and lead are extant, detailed information on extraction costs is missing. These industries declined in importance during the nineteenth century, and the 1907

Industrial Census only distinguishes employment in coal and iron mining. However this does mean that labour productivity in coal and iron mining, and average extraction costs per ton, can be gauged at this date. Methods of extraction in the smaller metal mining industries was similar to iron ore in the nineteenth century and changed little over this period, and thus labour costs per tonne are taken here to be the same for all mining of metals.

In the two centuries prior to 1960, the value of extracted mineral rents averaged around 2% of GDP, chiefly from coal mining. Thereafter coal rents became less important, but the extraction of North Sea oil pushed overall mineral rents to a peak of around 7% of GDP in the 1980s, then falling to around 2.5% of GDP in the 1990s. The extracted rental value of other minerals was low relative to GDP. That of iron ore peaked around 1870 at 0.65% of GDP and fell to around 0.05% by 1900. Collectively extracted rents from lead, zinc, tin and copper ores reached around 0.2% of GDP by 1850 but dwindled to around 0.02% by the 1920s.

2.3. GS: GREENINV plus changes in human capital

As with the World Bank methodology, we have incorporated public expenditure on schooling into our GS calculations as a proxy for investments in human capital. Data on public expenditure on education were derived from Carpentier [23] for the period 1833-1997, [8] and UNESCO measures thereafter. There are advantages and limitations to proxying the human capital by education expenditure. Investment in education fits naturally into the GS framework, which articulates the varying components of investment. However, human capital formation does not simply equate to education investment, since it includes, for

[8] Carpentier [24, 25] gives an English language overview of the methodology and findings of Carpentier [23].

example, skills acquired in the workplace. This problem is all the more significant in earlier periods before universal schooling, which was only established up until age 15 in the mid-twentieth century in the UK.[9] This partly explains the dramatic upward shift in education spending after WWII: public education investment averaged 0.76% of GDP 1765-1914 and rose through the twentieth century to average 4.3% of GDP 1946-2000.

2.4 GREENTFP and GSTFP: GREENINV and GS plus the value of changes in technological progress

Weitzman [26] and Pemberton and Ulph [27] advocated the inclusion of exogenous techological progress in assessments of the capital stocks of a country. Arrow et al [5] also include the value of technological progress as part of a country's capital stock. Pezzey [12] and Pezzey et al [16], refer to such technological progress as part of a "value of time passing", which increases the future consumption possibilities of an economy. They further argue shifts in the terms of trade for natural resource exports should be part of the value of time. The case for including exogenous technological progress within a more comprehensive investment measure appears strong in light of the widespread evidence that residual productivity plays a central role in the consumption growth of OECD countries [2]. In contrast there is no convincing evidence that the terms of trade favour natural resource exports over the long run [28], and we limit the augmenting of GS for the value of time to technological progress, using a measure of trend growth in total factor productivity, TFP.

An annual TFP index was constructed as follows:

[9] We are currently assembling an alternative data set for human capital based on discounted lifetime earnings. However there are conceptual and empirical problems with this approach too.

$$TFP = GDP/(Labour^{\alpha}\ Capital^{1-\alpha}) \quad (7)$$

where Labour is measured as hours worked, Capital is the stock of reproduced capital, and α is the elasticity of output with respect to labour. The resulting TFP index conforms to interpretations of British economic growth such as Crafts [29] and Voth [30], which show low TFP growth rates before the 1850s, and acceleration in the twentieth century. Trend TFP growth, was extracted from the annual index using the Kalman filter, and is shown as Figure 1.

Figure 1 near here

Trend growth TFP estimates can be used to underpin the valuation of exogenous technological progress. Arrow et al [5] simply augmented their measure of comprehensive investment with the current value of TFP, which shows how technological progress increases current income. Strictly, however, treating time as an uncontrolled capital stock means TFP's contribution to the change in wealth in any year should be included in our measure of GS. Our approach to gauging how TFP contributes to changes in the value of wealth follows Pezzey et al [16, Equation 14] but calculates the present value of future changes in TFP over 20 and 30 year horizons, to reflect the uncertainty over how long the value of technological progress persists, using both 2.5% per annum and 3.5% per annum discount rates (the choice of these rates is explained in section 3.1). The GSTFP sample period runs from 1765-1989; thus with the 30 year horizon trend grwoth TFP estimates are needed for the years 1765-2019. The estimates for 2008-19 data are based on an ARIMA forecast. According to this methodology, in the case of a 20 year horizon with a 2.5% per annum discount rate the value of discounted technological progress relative to the current value of GDP increases over time. 1765-1799 the average is 2.21%, 1800-1899 it is 7.85%, 1900-1949 it is 15.34%, and 1950-1999 it is 21.21%.[10] The contribution is less if we use a 3.5% per annum discount rate (averaging 1.82, 6.47, 12.63 and 17.55% of GDP for the same time-spans); however, using a 30 rather than a 20 year time horizon has little effect.

Treating technological progress as an uncontrolled stock of capital associated with the 'passing of time' which can be measured by TFP assumes that all technological progress is exogenous [27]. This is clearly not the case empirically, and part of the TFP might arise from, for example, R&D spending. A particular issue for the GSTFP measure is its inclusion of public education investment, which might be associated with endogenous technological change. This introduces an element of double-counting into the measure. Accordingly, our empirical tests also consider an alternative formulation of technology-augmented investment, GREENTFP, which adds the technological progress premium to GREENINV.

2.5 GSWPOP and GSTFPWPOP

The measure of aggregate wealth follows the World Bank [3, 8]'s 'top-down' construction method. FHV [10], alternatively, directly measure elements of aggregate wealth, but their approach is not followed here in the absence of complete information on individual wealth components, but we do utilize their concept of wealth dilution. The World Bank measure identifies wealth with the present value of an estimated stream of consumption over 25 years. Wherever possible our preference is to directly measure the elements of aggregate wealth. However, for testing the sensitivity of GS to possible wealth dilution associated with

[10] It is interesting to compare the size of this adjustment with Weitzman [26]: he found that a technological change premium could be as high as 40% of NNP. However, his figures are for a notional economy rather than real data.

population growth, there is no viable alternative to a top-down measure of aggregate wealth in the absence of complete human and social capital data. The underlying consumption data post-1870 is from estimates of national accounts [17, and ONS]. For earlier years measures of public spending and occasional estimates of the ratio of private consumption to GDP have been utilized as described in the Data Appendix.

2.6 Comparing the Investment Measures

The increasingly-comprehensive measures NETPINV, GREENINV, GS, GREENTFP, GSTFP, GSWPOP and GSTFPWPOP are illustrated as Figures 2, 3 and 4. The real value of British GS per capita and of GS as a percentage of GDP was mainly positive over the period 1765-2000, although both measures were negative during the World Wars.[11] GS rose during the Industrial Revolution from less than 2% of GDP in the 1760s, to around 5% by the 1850s, although there was a dip during the Napoleonic Wars. Natural resource depletion was offset by a rise in domestic fixed capital formation in the first half of the nineteenth century. In contrast, a rise in net overseas investment underpinned the continuing rise in the GS/GDP ratio in the period 1850-1910 to a peak of around 9%.

Figure 2 near here

Figure 3 near here

[11] Real GS per capita incorporates GDP deflators [22, 20] to convert to year 2000 prices.

The GS/GDP ratio fell during and between the World Wars, reflecting falls in domestic and overseas investment. The post-war recovery of the ratio to its 1960s peak of around 14% was driven by domestic fixed capital formation and higher investment in education. Subsequently, the ratio halved in the final quarter of the twentieth century as the extraction of oil rents surged and there was a relative fall in domestic capital formation. Continuingly high levels of education investment, which averaged around 5% of GDP in the period 1970-2000, ameliorated the decline in GS/GDP. The effects of augmenting GS with the value of technology are also most substantial in the second half of the twentieth century. Technology-augmented GS shows positive values throughout the period 1760-2000 and averages 29% of GDP from 1960 to 2000, using a 2.5% per annum discount rate, or 26% of GDP from 1960 to 2000 using a 3.5% per annum discount rate.

GS, adjusted for the wealth dilution (Figure 4) caused by distributing capital among a larger population, shows negative values over extended periods, including the whole of the nineteenth century. Indeed, only during the 1960s was GSWPOP persistently positive. These data need to be judged in the context of the top-down measure of wealth, which assumes a stable long-run relationship between consumption and wealth. However they highlight, in periods of sustained population growth which in Great Britain averaged around 1% per annum over the 150 years before 1914, that wealth dilution raised a high barrier to improving future well-being. Further, they highlight the potentially important role of new technology in offsetting wealth dilution, given that GSTFPWPOP is positive for most of the twentieth century.

Figure 4 near here

2.7 Measuring well-being over time

Following FHV [10], we have calculated the present value of future changes in consumption per capita as the well-being measure which accords most closely with the predictions of the theoretical framework for Genuine Savings. However, annual estimates of consumption are only extant from 1870 [17]. Longer runs of real wages are available, and we make use of the compilations reported in Measuring Worth [31]; given our desire to test the GS model with data from 1765. Three time horizons (20, 50, 100 years) and discount rates of 2.5% per annum and 3.5% per annum are used in the construction of both well-being measures. Figure 5 illustrates these data using a 2.5% per annum discount rate. Over shorter 20 year time horizons real wages can be volatile and they sometimes fall. The 100 year time horizon gives a smoother series, which must end in 1909 given that the actual wage series runs to 2009. One feature of the series using a 50 year time horizon is the marked rise in the PV of real wage increases from 1909, which chiefly reflects real wage shifts in the second half of the twentieth century.

Figure 5 near here

3. Estimation methods and test results

We now provide a discussion of the estimation methods and the results of the tests outlined in section 1.2 as applied to the various measures of GS and well-being outlined in section 2. Our empirical models adopt two, alternative measures of future well-being; real consumption per capita and average real wages, which are linked to increasingly-comprehensive measures of investment, including technology-augmented measures.

Consumption estimates are extant for years from 1870, whereas estimates of real wages cover the period 1765-2009.

3.1 Estimation methods

The long spans of the univariate macroeconomic time series data used in the estimation and testing of the various models have the potential to exhibit non-stationary properties. Thus, without appropriate methods, estimates may be inefficient or spurious and the usual significance tests may be invalid. Engle and Granger [77] show that a linear combination of two or more series that are integrated of order 1 may be stationary. The linear combination, if it exists, defines a cointegrating equation where the resulting vector characterizes the long-run relationship between the variables. A cointegration estimation approach: i) resolves the problem of non-stationary time series data and the inference issues of its neglect, ii) has the interpretation that the cointegrating relationship (if it exists) can be regarded as a (potentially) unique long-run economic equilibrium relationship, iii) has the properties that the estimates are 'super-consistent' i.e. they are consistent with much smaller sample sizes, iv) 'washes-out' in the long-run random errors that may exist in one or both series and, v) means inferences can be made on the levels of the series. If cointegration exists, the power of its long-run properties dominates short-run variations, which by definition are going to be stationary.

Cointegrating relationships, however, and their benefits and properties do not exist with all combinations of non-stationary series - there is a need to test for their existence. The two-step test used here appraises the time series properties of the residuals in a levels OLS regression, where the null hypothesis is of no-cointegration. The Engle-Granger method follows the OLS regression with a test of the error term's order of integration as step two. The residuals derived from the step-one process have the property of a generated regressor (Oxley and McAleer [78], Greasley and Oxley [79]). The critical values of the ADF test in the results' tables adjust for this property. A case of non-cointegration does not necessarily invalidate the results, but they are less robust. At this point we reiterate that in the results presented below we are specifically and only considering the results as tests of the size and signs of β_0 and β_1.

3. 2 Net produced, green and genuine investment and future real wages

Using the estimation and testing framework outlined above, we firstly consider the relationship between future real wages, produced investment (NETPINV), green investment (GREENINV) and Genuine Savings (GS). The dependent variable is the present value of the future changes in real wages over 20, 50 and 100 years. Accordingly, for the shortest 20 year time horizon, and given that the real wage series runs to 2009, the sample period of investment must be 1765-1989, and for the 100 year time horizon it is 1765-1909. The rate chosen to discount future changes in real wages has important implications, especially over the 100 year time horizon. We prefer a discount rate of 2.5% per annum which equates to the average real interest on long British government bonds 1765-2000, but to test sensitivity we also report results using 3.5% per annum, the average rate used by FV for their post-1970 panel of countries.

The results in Tables 2 and 3 shows that time horizons and discount rates have greater influence on the estimated parameters than the alternative investment measures.

Ostensibly the estimates for GREENINV and GS over the 100 years horizon with a 3.5% per annum discount rate give most support to the hypothesis of present investment indicating future real wages. In this case the weaker hypothesis $\beta1=1$ cannot be rejected where a cointegrating relationship has not been rejected. None of the results support the strong joint hypothesis $\beta0=0$; $\beta1=1$. The weaker hypothesis appears sensitive to the choice of discount rate, with all the estimated coefficients showing markedly higher values with a 2.5% per annum discount rate over the longest horizon. In the case of GS over the 100 year time horizon, the estimate of $\beta1=2.71$ suggests that investment leads to higher future well-being, discounted at 2.5% per annum, than theory predicts. If the theory holds, one possibility is that the GS measure does not fully capture or accurately measure all relevant investment. The other possibility is the value of future real wages, discounted at 2.5% per annum, does not properly measure future well-being.

Table 2 about here

Table 3 about here

3. 3 Net produced, green and genuine investment and future consumption per capita

The present value of changes in future consumption per capita provides an alternative measure of well-being which accords more closely with theory, but these data are only available from 1870. The estimates of β_1 over the 100 years consumption horizon using a

2.5% per annum discount rate show rising values of 0.4, 0.68 and 1.04 as the measure of net investment becomes more comprehensive, see Table 4. However, the statistical significance of the estimated parameters for GS needs to be treated with caution in the absence of cointegration. We only observe cointegration between GS and the PV of consumption change over the 20-year time horizon, but not for all other relationships, and none of the results are supportive of the stronger joint hypothesis.

Table 4 about here

3. 4 Investment, technology and future well-being

In their landmark paper, Ferreira and Vincent did not find that GS had positive and significant effects on the future consumption of OECD countries, a result they attribute to their measure of GS excluding technical change. Longer time horizons reinforce the importance of including technology in measures of wealth. A series of theoretical papers have shown how omitting technological progress from the calculation of GS can be misleading [5, 12 and 26]. Table 5 reports the estimated parameters, in the case of the value of future consumption, from augmenting GREENINV and GS with the value of technological progress, using the alternative indicators discussed in section 2.4. As GS includes expenditures on education, which may be partially reflected in TFP, using the two measures GREENTFP and GSTFP sheds light on possible double counting.

The technology-augmented results provide strong support for the weakest and, in one case, for the strong hypotheses, most especially over the 100 year time horizon. The estimates of β_1 are closest to 1 in the case of GSTFP30, that is a measure where GS is augmented by "the value of time" introduced by exogenous technological change with effects lasting 30 years. Over a 100 year time horizon, we find that the difference between GREENTFP and GSPTFP is negligible in the case of the weaker hypothesis. In contrast to the results without including TFP, the null of no-cointegration cannot be rejected for any TFP-augmented results over 100 year time horizons. The strong joint hypothesis is not rejected for GSTFP30, although the intercept individually is significantly different from zero.

Table 5 about here

The results in table 6, where we use the alternative real wage-based measure of well-being, reinforce the case for augmenting investment with the value of technological progress. In particular the estimates of β_1 are in the range 1.16-1.37 for the 100 year time horizon. While all these estimates are significantly different to 1, the contrast is marked with the results obtained without including any augmentation from technological progress displayed in Table 2, which are in the range 2.39-2.71. Nevertheless, the real wage-based results are not so clearly in favor of the weaker hypothesis as those utilizing consumer spending as a measure of well-being. This may partly reflect issues of data quality as the samples are pushed back to 1765 in the former but begin only after 1870 with the latter. However, over the long run changes in income distribution have probably favored wage earners. If so, current investment would have a larger effect on future real wages than on future consumption.[12] One outlier in Table 6 is the GREENTFP20 result over the 20 year time horizon using real wages, which does not reject the strong hypothesis.

[12] We are grateful to a referee who suggested unionization may have been an influence on UK income distribution over the sample period. Other distribution influences include import prices and tax rates, for a full

Table 6 about here

3.5 Truncating the investment sample period

Our core results utilize the longest samples feasible for each well-being horizon to investigate how well the theory (which is based on infinite horizons) holds up over the very long-run. A downside of using the longest feasible samples when assessing if β_1 tends to 1 as horizons extend is that the varying sample size may influence outcomes. Accordingly, the results of Table 7 (and 8) truncate all investment samples at 1909, irrespective of the well-being horizon.

Table 7 about here

With the investment samples confined to the period 1870-1909, the progressive extension of the horizon for future changes in consumption to 100 years yields estimates of β_1 that become closer to 1. This finding applies to the results with and without augmentation for technological change. Although GS, GSPTFP20 and GSTFP30 have estimates of β_1 that are closer to 1, they cannot be considered statistically robust with no-cointegration not rejected. Investment samples from the period 1765-1909 always over-predict future real wages in the variants without technology: over any time horizon future real wages were higher than GS predicts. With technology included, the estimates of β_1 are in the range of 0.64-1.36 and rise with longer horizons. Those at the 50 year time horizon are closest to 1,

discussion see Matthews et al [32] chapter 6. Real wages grew faster than consumption per capita 1870-2009, at 1.48% per year compared to 1.37% per year.

and the higher values with 100 year time horizon are likely to reflect that real wages grow more quickly than consumption per capita over the long-run.

Table 8 about here

3. 6 Adjusting Genuine Savings for Wealth Dilution

In contrast to the finding of FHV, our results show adjusting the various investment measures for wealth dilution has a considerable effect on the estimated parameters, see Table 9. This may be due in part to differences in the estimation of aggregate wealth since FHV use a direct but partial measure rather than the 'top down' World Bank approach of our study. Accounting for wealth dilution (see Figure 4 above) diminishes GS to negative values for long periods before 1945, although GSTFP ameliorates the effect. Without the TFP adjustment, the estimated β_1 parameters show a high degree of variation over the different well-being horizons. The large negative value, for example for GS-WPOP over the 100 year time horizon reflects this measure of investment is falling up until 1909 while future well-being measured up to 2009 rises.

The wealth-adjusted results reinforce the importance of augmenting GS with technological progress. In the TFP variants illustrated in Table 9, all the β_1 estimates are positive and fall within the range 0.71 to 2.41. Over the 100 year time horizon especially these estimates are considerably higher at 1.81 and 2.41, compared to the comparable estimates without the adjustment for wealth dilution of 1.15 and 1.20, see Table 8. A likely implication of these results is that the wealth adjustment overstates the detrimental effects of dilution on future well-being, which in turn might arise from wealth measurement errors. In particular the measure of aggregate wealth rests on assumptions of the wealth to consumption ratio which may not hold over the very long-run.

Table 9 about here

4 Discussion and Concluding Remarks

The main contribution of this paper has been to undertake the first long-run test of the performance of Genuine Savings (GS) as an indicator of changes in future well-being. We constructed a British GS series back to 1765, and then tested how well GS indicates changes in future well-being over time periods of up to 100 years. For two alternative future well-being measures (real wages and consumption per capita) our results conform more closely with the theoretical relationship between GS and future well-being, and provide stronger support for the indicative capacity of the GS model, than has been found by previous authors. In particular they show the value of extending the well-being horizon to a period of 100 years and of incorporating a measure of technological progress in GS. The weaker sustainability hypothesis of a one to one relation (β_1=1) between more inclusive measures of net investment and future well-being receives some support from our findings, although we typically reject the stronger joint hypothesis $\beta_0 = 0$ and $\beta_1 = 1$.

However a number of caveats need to be highlighted. Our longest sample results utilize real wages to measure future well-being, and these data show some discrepancies with estimates using of consumption per capita, although the latter should accord more closely with the underlying theory. Some elements of the pre-1870 data, including produced investment, are based upon decadal estimates. On balance our view is that the tests with the longest runs of data have utility, and their outcomes generally conform to the results based upon post-1870 data. An important issue for gauging future well-being over long horizons concerns the choice of discount rates. The results are sensitive to the discount rate, especially, unsurprisingly, over the longest 100 year time horizon. The preferred rate of 2.5% per annum used here reflects the real interest paid on British government long-term debt since 1765.

Incorporating the value of exogenous technology in measures of GS has substantial effects on some variants of the results, although in the case of future change in consumption it is the short horizon results that are most affected. Over the 100 year time horizon the estimates of β_1 for both GS and the technology-augmented measure of GSTFP match closely. For future changes in real wages, the technology-augmented measures yield estimated parameters more closely aligned with theory than others measure of net investment. Previous tests of GS's indicative capacity have omitted a role for technology, but the results here support its inclusion in long run tests of sustainability, although complex issues surround its measurement.

The exogenous measure of technological progress used here rests on estimates of TFP. In principle an endogenous measure of technology could be incorporated, as discussed by Pemberton and Ulph [27], and research in this area might prove fruitful, using for example measures of R&D. Constructing long series for investment in technology are currently not feasible. Those who are sympathetic to endogenous interpretations of economic growth do not deny that important elements of technological progress may be exogenous [33].

However, GS includes elements of investment, notably human capital formation, which might be reflected in the measure of residual productivity. While a good case can be made for incorporating a measure of residual productivity in GS there is no consensus how it should be done [5, 34].

Strictly it is the value of technological progress to changes in the stock of wealth that needs to be gauged and added to GS [11]. Pezzey et al [16] propose a measure which utilizes the discounted future value of TFP, although they give no firm guidance on the horizon or the choice of discount rate. In light of the uncertainty surrounding the longevity of the value of technological progress, two horizons were used here, of 20 and 30 years, but the empirical differences appeared negligible. Furthermore, two technology-augmented measures, GREENTFP and GSTFP were also used in empirical tests, with the former designed to avoid the double counting of residual productivity. Again, in the empirical tests, only minor differences between estimates were found. Alternatives to exogenous measures of technological progress are worth investigation, but the results here show exogenous measures have utility.

At present, we follow the World Bank approach and measure changes in human capital via public investment in education. Yet for much of the time period under consideration, most workers spent little time in school, and thus public educational investments are unlikely to be good measures of their capacities [37]. It is thus important to investigate other ways of measuring changes in the human capital stock, for example appraoches based around discounted lifetime earnings [38]. Preliminary analysis for the UK shows that a discounted lifetime earnings approach would produce far higher estimates of the human capital stock than the expenditures on education approach [39].

There are also other enhancements that could be made to the ways in which GS are calculated. One is in the measurement of wealth. The top down approach used by necessity here probably overstates the capital dilution associated with a higher population. Nor is pollution presently included in our GS calculations. Whilst CO_2 emissions were rising over the period of our analysis, it is questionable how significant the resultant damages per unit of emission were over almost all of our period, since global stocks of greenhouse gases were far below critical levels. Rather more importantly for the time period under considerations, emissions of conventional pollutants such as particulates had a major impact on health [35, 36]. Using a discounted lifetime's earnings approach to human capital would allow the impact of air pollution on workers to be directly included in GS calculations. Finally, we note that future work, which enhanced the coverage of historical data to more aspects of natural capital changes, would be desirable.

Data appendix:

Appendix Table 1: Descriptive Statistics for Key Variables

	Count	Mean	Standard Deviation	Minimum	Maximum
NETPINV	224	239.24	278.03	-727.78	1066.04
GREENINV	224	157.36	258.07	-824.01	1003.52
GS	224	247.12	360.73	-743.18	1472.60
GREENTFP20	224	815.17	917.13	23.25	3654.60
GREENTFP30	224	997.67	1105.80	34.49	4456.49
GSTFP20	224	904.92	1067.23	23.25	4219.93
GSTFP30	224	1087.42	1256.52	34.49	5021.83
GSWPOP	224	-267.37	424.76	-1516.07	1422.01
GSTFP20WPOP	224	390.43	1117.66	-664.04	3807.49
PVΔCons20	121	826.6887	886.3903	-136.206	3247.617
PVΔCons50	91	826.3648	728.5775	118.1688	2499.604
PVΔCons100	41	498.7835	187.7609	246.6412	821.1678
PVΔRW20	225	833.7201	970.2563	-568.069	3406.722
PVΔRW50	195	886.4572	868.6192	67.91884	3291.732
PVΔRW100	145	458.1318	302.2781	87.97897	1180.489

Note: The present value of future changes in consumption, real wages and TFP is discounted at 2.5% per annum. All variables are expressed as £ per capita in 2000 prices.

GDP and GDP deflator: Nominal GDP 1765-1870 from Broadberry *et al* [22]; 1870-2010 from *Measuring Worth*, http://www.measuringworth.com/ukgdp/ and last accessed June 2013. Full details of the income, output and expenditure estimates adopted in the post- 1870 data are listed in Officer, What Was the UK GDP Then: A Data Study, accessible from the Measuring Worth site. The GDP deflator is from the same sources.

Population: 1830-2010 is calculated using the *Measuring Worth* UK population data minus the populations of Ireland from 1830-1920 and Northern Ireland from 1921-2010. 1750-1830 is from Wrigley's [40] annual population estimates of England and Wales, combined with those for Scotland, derived from Flinn [41] and Census of Scotland from 1801 onwards.

NETPINV: 1765-1920 is from Feinstein and Pollard [19], 1921-65 from Feinstein [17]. 1966-2000 is from UK ONS publications. For the period 1760-1855 NFCF and inventories were reported as decadal averages as was net overseas investment 1760-1870. In both cases annual estimates are interpolated.

GREENINV: *Forestry*: Stock estimates for the woodland area (hectares) and standing volume (cubic metres per hectare) are from British agricultural returns, Schlich [42], Stamp and Beaver [43], the 1923 and 1947 woodland censuses, Eurostat and the UK Forestry Commission. International trade prices per cubic metre are used to value the standing volume given Great Britain was a net importer of timber. A variety of prices estimates are combined, including UK import prices from 1760-1810 and 1847-1957, Finnish export prices from 1810-1847, and US export prices from 1965-2000 [44-52]. Average prices are used in the absence of the single long run series, for details see McLaughlin et al [18]. Felling costs are estimated as wage costs per m^3. MacGregor [53 p.30] shows labour costs were the 'greatest direct influence on the cost of forestry operations', but he reports daily rates, not the cost per m^3. Labour costs per m^3 are estimated from the employment of felling and forest workers and annual felling. Employment in forestry has been estimated for 1765-1840 assuming 5 workers per 100 acres [54], based on Heske's [55] claim that each 35 cubic feet of wood cut needed one day's work. Census data provides employment of woodcutters from 1841 to 1921 as do Forestry Commission reports for later years. The felling data used to construct the estimates of wage costs per m^3 are from [56, 50] and Forestry Statistics 2001.

Minerals: Coal: Estimates of coal extraction are from [57-61] and from *UK Mineral Statistics and UK Mineral Yearbook*. Pithead prices per tonne are from [59-64], NCB reports, *UK Mineral Statistics* and *UK Mineral Yearbook*. Wage estimates were taken from [58-61, 64] and National Coal Board reports. The nineteenth century data are for hewers and were reported as daily wages in [58] and shift rates in both [61] and [59]. Labour force numbers were taken from the *Annual Returns of Mines* from 1874 onwards [60], from census returns [60, 65], and estimated assuming productivity of 250 tons per worker for years to 1874.

Iron Ore: Extraction data are from the official series beginning in 1854 and earlier estimates from [66, 67]. Mine-head prices from 1854 onwards are also reported in the *Mineral Statistics*. The integrated organisational structure of the British iron industry makes it difficult to ascertain iron ore prices pre-1854. We assume the price of iron ore was a ratio of the price of pig iron, adopting 10% of the pig iron price, which was the average ratio 1857-1914. British iron production dwindles in importance by 1900, and US prices are used for the period 1915-2000, taken from Kelly *et al*. [68], to value the small quantities of British production. Daily wage rates across all the mining industries were similar [69], though wage costs per ton differed. From the 1907 census of production output per man year (OMY) for iron ore miners was 611 tons [70] versus an OMY of 321 tons for coal miners [71]. Labour productivity in iron ore mining was around twice that of coal and therefore their labour costs per ton would have been about half that of coal mining. We use this relativity to estimate wage costs per ton for iron ore mining. Data on tin, copper, lead and zinc extraction are from Mitchell [60] and *UK Mineral Statistics* and *Mineral Yearbooks*. There are no separate employment data for these mining operations and wage costs per ton, given the similar extraction technology, are assumed equal to those for iron ore mining.

Oil and gas: extraction estimates are from *Energy Trends* 2002. Historic oil prices per barrel are from the BP *Statistical Review of World Energy* and converted to price per tonne, taking a barrel to equal to 0.136 tonnes. Dollar prices are converted to pounds with the historic exchange rates from Officer [72]. The marginal costs of oil and gas extraction are assumed to be zero.

GS**:** The education investment data are from Carpentier [23].

***GSTFP**: TFP*: real gross capital stock is from Feinstein [17, 19] and O'Mahony [73]. Labour hours are from Crafts [29], Voth [30], Wrigley [40], Flinn [41], Feinstein [17], and O'Mahony [73].Factor shares, which are used to measure the output elasticities assuming wages equate to marginal product of labour, are from Crafts [29], Matthews et al [32] and ONS [74]. The factor shares are: 1760-1860, α= 0.50; 1856-1920, α=0.58; 1920-1951, α=0.70; 1951-1973, α=0.73; 1973-2000, α=0.64. Annual TFP has been calculated except for 1760 to 1860 where an annual series has been interpolated from decadal data. The trend growth TFP is a Kalman filter of the TFP growth rate. TFP trend growth post 2007 is forecast using an ARIMA (3,1,3) forecast.

Wealth: Wealth is the present value of a 3 year average of consumption (government and private) at constant prices over 25 years. Post-1870 consumption data are from Feinstein [17] and ONS. For earlier years public consumption and private consumption are based on occasional estimates of consumption and GDP. From 1760 to 1869 consumption has been estimated as a constant 93.52% share of GDP, which is the average for 1870 to 1900. The choice of discount rate follows World Bank [3, 8] and uses a 1.5% per annum rate of pure time preference.

Future well-being: *Real Wages*: These are from Measuring Worth. Full details of the component series are discussed in Clark [31], accessible via the Measuring Worth site. Present values are constructed utilizing a 2.5% per annum discount rate which equates to the average interest on British government long bonds 1765-2000 less retail price inflation, as reported by Measuring Worth. *Consumption:* The post-1870 estimates are from Feinstein [17] and ONS.

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Tables

Table 1 : Net Produced Investment as % GDP 1760-2000

	NFCF	*Inventories*	*Net Domestic*	*Net Overseas*	*NETPINV*
1760-1860	2.64	1.08	3.72	1.15	4.87
1860-1914	3.73	0.74	4.47	4.70	9.17
1914-1918	0.07	-0.62	-0.55	0.21	-0.34
1918-1938	2.39	0.01	2.40	0.82	3.22
1939-1945	-0.91	-0.20	-0.71	-7.56	-8.27
1946-1968	7.42	0.96	8.38	0.01	8.39
1946-2000	7.06	0.60	7.66	-0.22	7.44

Note: NFCF is net domestic fixed capital formation. Sources: see Data Appendix.

Table 2: Estimates of β_0 and β_1 for three Investment series and future real wages (2.5% per annum discount rate)

1.	2.	3.	4.	5.	6.	7.
Dependent	Independent	β_0	β_1	$\beta_0=0$; & $\beta_1=1$	$\beta_1=1$	ADF
Real Wage 20 years	NETPINV	280.3* (63.9)	2.32* (0.174)	208.4* (0.00)	57.2* (0.00)	-3.59*
Real Wage 50 years		827.1* (81.2)	0.37 (0.33)	141.1* (0.00)	3.51** (0.06)	0.48
Real Wage 100 years		68.2* (24.4)	2.39* (0.13)	608.8* (0.00)	123.1* (0.00)	-5.10*
Real Wage 20 years	GREENINV	579.4* (68.5)	1.62* (0.23)	141.4* (0.00)	7.49* (0.01)	-2.84
Real Wage 50 years		906.9* (70.9)	-0.20 (0.33)	171.4* (0.00)	13.0* (0.00)	1.08
Real Wage 100 years		108.7* (23.7)	2.89* (0.16)	732.2* (0.00)	140.7* (0.00)	-6.21*
Real Wage 20 years	GS	377.9* (57.0)	1.85* (0.13)	198.3* (0.00)	42.4* (0.00)	-3.56*
Real Wage 50 years		776.7* (73.7)	0.81* (0.31)	151.1* (0.00)	0.37 (0.54)	-0.08
Real Wage 100 years		108.9* (19.9)	2.71* (0.12)	967.2* (0.00)	199.0* (0.00)	-7.13*

Notes: Dependent = the present values of future changes in real wages measured over 20-100 year horizons. For column 3, H_0: $\beta_0=0$; H_1: $\beta_0\neq0$ and for column 4 H_0: $\beta_1=0$; H_1: $\beta_1\neq0$ are tested using a 't' test where * denotes significantly different from zero at the 5% level and ** at the 10% level. For columns 3 and 4 figures in parentheses are standard errors. For column 5 H_0: $\beta_0=0$ and $\beta_1=1$; H_1: $\beta_0\neq0$ and $\beta_1\neq1$ are tested jointly using a Wald test where * denotes significantly different from zero and unity respectively at the 5% level. For column 6, H_0: $\beta_1=1$; H_1: $\beta_1\neq1$ is tested using a Wald test where * denotes significantly different from unity at the 5% level. For columns 5 & 6 figures in parentheses refer to p values for the Wald test where the test statistic is distributed as χ^2 with 2 (column 5) or 1 (column 6) degrees of freedom respectively. In column 7 ADF represents the Augmented Dickey Fuller statistic (corrected for the problem of Generated Regressors) where the degree of augmentation is determined by the Hannan-Quinn Information Criteria. A * represents rejects the null of non-stationary residuals at the 5% level and ** at the 10% level.

Table 3: Estimates of β_0 and β_1 for three Investment series and future real wages (3.5% per annum discount rate)

1.	2.	3.	4.	5.	6.	7.
Dependent	Independent	β_0	β_1	β_0=0; & β_1=1	β_1=1	ADF
Real Wage 20 years	NETPINV	230.8* (52.6)	1.91* (0.15)	166.5* (0.00)	40.2* (0.00)	-3.59*
Real Wage 50 years		509.0* (49.9)	0.23* (0.20)	117.1* (0.00)	14.1* (0.00)	0.48
Real Wage 100 years		25.8* (9.25)	0.90* (0.05)	8.15* (0.00)	4.03* (0.00)	-5.01*
Real Wage 20 years	GREENINV	477.1* (56.4)	1.34* (0.18)	124.2* (0.00)	3.22** (0.07)	-2.58
Real Wage 50 years		558.2* (43.7)	-0.12 (0.20)	163.8* (0.00)	30.2* (0.00)	-1.08
Real Wage 100		41.2* (9.00)	1.09* (0.06)	102.9* (0.00)	2.45 (0.18)	-6.22*
Real Wage 20 years	GS	311.2* (46.9)	1.52* (0.11)	153.0* (0.00)	23.75* (0.00)	-4.00*
Real Wage 50 years		478.0* (45.3)	0.50* (0.19)	125.9* (0.00)	7.14* (0.00)	-0.52
Real Wage 100 years		41.24* (7.43)	1.02* (0.05)	99.6* (0.00)	0.37 (0.54)	-7.13*

See Table 2 notes for explanations of null/alternative hypotheses and levels of significance.

Table 4*:* Estimates of β_0 and β_1 for three Investment series and future consumption (2.5% per annum discount rate)

1.	2.	3.	4.	5.	6.	7.
Dependent	Independent	β_0	β_1	β_0=0; &	β_1=1	ADF
Cons 20	NETPINV	322.9*	1.46*	56.2*	5.3*	-2.59
		(96.4)	(0.19)	(0.00)	(0.02)	
Cons 50		871.8*	-0.22	81.5*	16.3*	0.01
		(98.9)	(0.30)	(0.00)	(0.00)	
Cons 100		381.6*	0.40	52.5*	2.19	-0.50
		(120.9)	(0.40)	(0.00)	(0.14)	
Cons 20	GREENINV	684.6*	0.65*	61.7*	2.33	-0.73
		(94.2)	(0.23)	(0.00)	(0.13)	
Cons 50		862.1*	-0.28	104.0*	20.1*	0.11
		(84.5)	(0.28)	(0.00)	(0.00)	
Cons 100		348.7*	0.68	95.3*	0.75	-1.25
		(87.0)	(0.37)	(0.00)	(0.39)	
Cons 20	GS	383.7*	1.14*	44.7*	0.91	-3.17**
		(88.3)	(0.15)	(0.00)	(0.34)	
Cons 50		787.6*	0.20	76.2*	8.46*	-0.02
		(93.7)	(0.28)	(0.00)	(0.00)	
Cons 100		241.3*	1.04*	91.8*	0.02	-2.33
		(81.3)	(0.31)	(0.00)	(0.90)	

Notes: Dependent = the present values of future changes in real consumption per capita measured over 20-100 year horizons. See Table 2 notes for explanations of null/alternative hypotheses and levels of significance.

Table 5*:* Estimates of β_0 and β_1 for technology-augmented Investment series and future consumption (2.5% per annum discount rate)

1.	2.	3.	4.	5.	6.	7.
Dependent	Independent	β_0	β_1	β_0=0; & β_1=1	β_1=1	ADF
Cons 20	GREENTFP20	-227.4*	0.79*	192.3*	26.9*	-4.25*
		(66.6)	(0.04)	(0.00)	(0.00)	
Cons 50		-253.0*	1.29*	14.7*	14.6*	-2.53
		(72.9)	(0.07)	(0.00)	(0.00)	
Cons 100		-128.3	1.13*	6.46*	0.47	-3.49*
		(111.3)	(0.19)	(0.04)	(0.49)	
Cons 20	GSTFP20	-202.0*	0.69*	434.7*	96.8*	-4.33*
		(60.1)	(0.03)	(0.00)	(0.00)	
Cons 50		-248.3*	1.18*	13.2*	7.83*	-2.51
		(69.1)	(0.06)	(0.00)	(0.00)	
Cons 100		-148.3	1.12*	17.0*	0.56	-3.93*
		(93.6)	(0.16)	(0.00)	(0.45)	
Cons 20	GREENTFP30	-294.1*	0.68*	596.5*	100.2*	-4.23*
		(63.7)	(0.03)	(0.00)	(0.00)	
Cons 50		-383.5*	1.14*	80.3*	9.09*	-2.85
		(56.8)	(0.04)	(0.00)	(0.00)	
Cons 100		-190.6*	1.01*	68.7*	0.25	-4.19*
		(85.3)	(0.13)	(0.00)	(0.61)	
Cons 20	GSTFP30	-260.9*	0.60*	1041.4*	234.3*	-4.28*
		(58.4)	(0.03)	(0.00)	(0.00)	
Cons 50		-362.2*	1.05*	124.2*	1.50	-2.75
		(55.3)	(0.04)	(0.00)	(0.22)	
Cons 100		-177.2*	1.00*	114.5*	0.00	-4.38*
		(72.9)	(0.10)	(0.00)	(0.97)	

Notes: Dependent = the present values of future changes in real consumption per capita measured over 20-100 year horizons. The measures GREENTFP and GSTFP augment GREENINV and GS using a 2.5% per annum discount rate for the value technological progress over both 20 and 30 year time horizons, labeled GREENTFP20/30 and GSTFP20/30. See Table 2 notes for explanations of null/alternative hypotheses and levels of significance.

Table 6: Estimates of β_0 and β_1 for technology-augmented Investment series and future real wages (2.5% per annum discount rate)

1.	2.	3.	4.	5.	6.	7.
Dependent	Independent	β_0	β_1	β_0=0; & β_1=1	β_1=1	ADF
Real Wage 20 years	GREENTFP20	48.5* (35.4)	0.97* (0.29)	1.96 (0.38)	1.26 (0.26)	-4.58*
Real Wage 50 years		65.7 (40.9)	1.64* (0.06)	370.8* (0.00)	116.4* (0.00)	-3.20**
Real Wage 100 years		44.6* (18.2)	1.37* (0.05)	293.8* (0.00)	53.7* (0.00)	-4.09*
Real Wage 20 years	GSTFP20	85.0* (34.7)	0.83* (0.24)	52.7* (0.00)	46.1* (0.00)	-4.30*
Real Wage 50 years		84.5* (38.7)	1.50* (0.05)	266.6* (0.00)	94.0* (0.00)	-3.14**
Real Wage 100 years		50.8* (16.3)	1.30* (0.04)	311.4* (0.00)	52.0* (0.00)	-4.39*
Real Wage 20 years	GREENTFP30	32.7 (34.7)	0.81* (0.02)	107.7* (0.00)	68.9* (0.00)	-4.28*
Real Wage 50 years		25.7 (32.1)	1.38* (0.04)	250.9* (0.00)	104.9* (0.00)	-3.27*
Real Wage 100 years		31.9* (15.9)	1.20* (0.37)	171.8* (0.00)	29.6* (0.00)	-4.27*
Real Wage 20 years	GSTFP30	66.5* (33.3)	0.71* (0.02)	291.6* (0.00)	198.4* (0.00)	-4.07*
Real Wage 50 years		48.1 (31.2)	1.28* (0.03)	183.0* (0.00)	67.3* (0.00)	-3.30**
Real Wage 100 years		40.2* (14.5)	1.16* (0.03)	163.7* (0.00)	22.1* (0.00)	-4.50*

See Tables 2 and 5 notes for explanations of the variables and hypothesis tests.

Table 7: Estimates of β_0 and β_1 for seven Investment series and future consumption (2.5% per annum discount rate) and 1870-1909 sample

1.	2.	3.	4.	5.	6	7.
Dependent	Independent	β_0	β_1	β_0=0; & β_1=1	β_1=1	ADF
Cons 20	NETPINV	198.9*	-0.10	65.1*	20.3*	-1.77
		(73.0)	(0.24)	(0.00)	(0.00)	
Cons 50		174.0*	0.21	48.5*	26.0*	-1.34
		(46.0)	(0.15)	(0.00)	(0.00)	
Cons 100		369.0*	0.47	56.2*	1.76	-0.93
		(119.4)	(0.40)	(0.00)	(0.18)	
Cons 20	GREENINV	224.5*	-0.25	38.3*	29.9*	-2.05
		(53.3)	(0.23)	(0.00)	(0.00)	
Cons 50		184.6*	0.23	30.2*	28.2*	-1.31
		(33.7)	(0.14)	(0.00)	(0.00)	
Cons 100		344.7*	0.73*	101.6*	0.56	-1.57
		(85.4)	(0.36)	(0.00)	(0.45)	
Cons 20	GS	261.9*	-0.37	66.9*	46.5*	-2.40
		(52.7)	(0.20)	(0.00)	(0.00)	
Cons 50		164.1*	0.29*	32.3*	31.2*	-1.41
		(33.2)	(0.13)	(0.00)	(0.00)	
Cons 100		243.8*	1.06*	98.9*	0.03	-2.54
		(79.5)	(0.30)	(0.00)	(0.85)	
Cons 20	GREENTFP20	392.2*	-0.40*	638.5*	92.0*	-2.59
		(82.4)	(0.15)	(0.00)	(0.00)	
Cons 50		74.4	0.29*	1010.3*	59.6*	-1.77
		(51.7)	(0.09)	(0.00)	(0.00)	
Cons 100		-119.9	1.13*	5.32**	0.47	-3.63*
		(108.3)	(0.19)	(0.07)	(0.49)	
Cons 20	GSTFP20	399.5*	-0.39*	775.4*	120.4*	-2.61
		(75.4)	(0.13)	(0.00)	(0.00)	
Cons 50		75.4	0.28*	1241.5*	81.3*	-1.80
		(47.5)	(0.08)	(0.00)	(0.00)	
Cons 100		-136.4	1.10*	15.2*	0.48	-4.01*
		(91.3)	(0.15)	(0.00)	(0.49)	
Cons 20	GREENTFP30	414.6*	-0.38*	1075.6*	150.9*	-2.58
		(74.4)	(0.11)	(0.00)	(0.00)	
Cons 50		71.4	0.25*	1806.8*	109.5*	-1.85
		(47.3)	(0.07)	(0.00)	(0.00)	
Cons 100		--176.9*	1.05*	66.0*	0.17	-4.26*
		(83.4)	(0.13)	(0.00)	(0.68)	
Cons 20	GSTFP30	410.5*	-0.36*	1248.8*	185.9*	-2.54
		(68.9)	(0.09)	(0.00)	(0.00)	
Cons 50		77.1**	0.24*	2109.5*	144.6*	-1.82
		(44.0)	(0.06)	(0.00)	(0.00)	
Cons 100		-163.2*	0.99*	111.8	0.01	-4.44*
		(71.5)	(0.10)	(0.00)	(0.92)	

See Tables 2 and 5 notes for explanations of the variables and hypothesis tests.

***Table 8:* Estimates of β_0 and β_1 for seven Investment series and future real wages (2.5% per annum discount rate) and 1765-1909 sample**

1.	2.	3.	4.	5.	6.	7.
Dependent	Independent	β_0	β_1	β_0=0; & β_1=1	β_1=1	ADF
Real Wage 20	NETINV	13.7	1.71*	64.5*	16.4*	-3.89*
		(34.0)	(0.17)	(0.00)	(0.00)	
Real Wage 50		144.1*	1.81*	643.5*	57.4*	-5.81*
		(20.8)	(0.10)	(0.00)	(0.00)	
Real Wage 100		68.2*	2.39*	608.8*	123.0*	-5.11*
		(24.4)	(0.13)	(0.00)	(0.00)	
Real Wage 20	GREENINV	71.8*	1.82*	85.7*	12.7*	-3.63*
		(34.4)	(0.23)	(0.00)	(0.00)	
Real Wage 50		184.7*	2.10*	707.8*	59.2*	-5.98*
		(21.4)	(0.14)	(0.00)	(0.00)	
Real Wage 100		108.8*	2.89*	732.2*	140.7*	-6.22*
		(23.7)	(0.16)	(0.00)	(0.00)	
Real Wage 20	GS	95.2*	1.52*	69.9*	6.44*	-3.36**
		(34.0)	(0.21)	(0.00)	(0.01)	
Real Wage 50		200.8*	1.85*	642.7*	43.3*	-5.32*
		(20.9)	(0.13)	(0.00)	(0.00)	
Real Wage 100		108.9*	2.71*	967.2*	199.1*	-7.13*
		(19.6)	(0.12)	(0.00)	(0.00)	
Real Wage 20	GREENTFP20	34.7	0.85*	2.72	2.41	-3.35**
		(35.2)	(0.09)	(0.26)	(0.12)	
Real Wage 50		136.7*	1.00*	182.6*	0.00	-4.61*
		(18.3)	(0.04)	(0.00)	(0.99)	
Real Wage 100		44.6*	1.36*	293.8*	53.7*	-4.09*
		(18.6)	(0.05)	(0.00)	(0.00)	
Real Wage 20	GSTFP20	50.4	0.78*	6.59*	5.71*	-3.14**
		(35.0)	(0.09)	(0.04)	(0.02)	
Real Wage 50		149.6*	0.93*	153.3*	1.84	-4.31*
		(18.5)	(0.05)	(0.00)	(0.17)	
Real Wage 100		50.9*	1.31*	311.3*	52.0*	-4.39*
		(16.2)	(0.04)	(0.00)	(0.00)	
Real Wage 20	GREENTFP30	46.4*	0.69*	22.1*	12.6*	-3.28**
		(36.4)	(0.08)	(0.00)	(0.00)	
Real Wage 50		136.5*	0.86*	79.4*	10.4*	-4.21*
		(18.8)	(0.04)	(0.00)	(0.00)	
Real Wage 100		31.9*	1.20*	171.8*	29.7*	-4.28*
		(15.9)	(0.04)	(0.00)	(0.00)	
Real Wage 20	GSTFP30	60.4**	0.64*	30.6*	18.8*	-3.02
		(36.1)	(0.08)	(0.00)	(0.00)	
Real Wage 50		149.2*	0.80*	73.6*	20.4*	-3.97*
		(19.1)	(0.04)	(0.00)	(0.00)	
Real Wage 100		40.2*	1.15*	163.7*	22.1*	-4.49*
		(14.6)	(0.03)	(0.00)	(0.00)	

See Tables 2 and 5 notes for explanations of the variables and hypothesis tests.

Table 9*: Estimates of β_0 and β_1 for wealth-dilution adjusted Investment series and future real wages (2.5% per annum discount rate)*

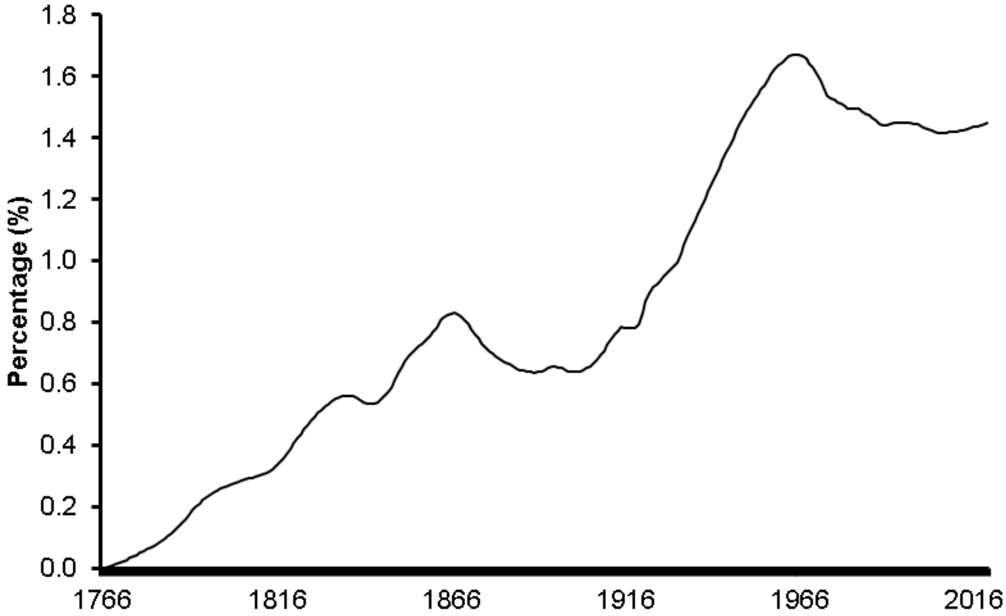
1.	2.	3.	4.	5.	6.	7.
Dependent	Independent	β_0	β_1	β_0=0; & β_1=1	β_1=1	ADF
Real Wage-Wealth 20y	NETPINV-WPOP	1301.8* (78.8)	1.44* (0.17)	385.9* (0.00)	6.27* (0.01)	-4.89*
Real Wage-Wealth 50y		1090.0* (133.7)	-0.33 (0.30)	554.8* (0.00)	19.6* (0.00)	0.59
Real Wage-Wealth 100y		-313.1* (152.4)	-4.18* (0.37)	1521.5* (0.00)	197.4* (0.00)	-3.37*
Real Wage-Wealth 20y	GREENINV-WPOP	1302.0* (97.4)	1.15* (0.20)	375.2* (0.00)	0.58 (0.44)	-3.86*
Real Wage-Wealth 50y		913.6* (141.4)	-0.69* (0.28)	622.1* (0.00)	35.5* (0.00)	0.67
Real Wage-Wealth 100y		-411.4* (137.5)	-4.00* (0.30)	1927.7* (0.00)	278.2* (0.00)	-3.52*
Real Wage-Wealth 20y	GS-WPOP	1266.2* (69.6)	1.34* (0.14)	418.2* (0.00)	6.15* (0.01)	-4.91*
Real Wage-Wealth 50y		1175.7* (134.9)	-0.10* (0.28)	564.9* (0.00)	15.0* (0.00)	0.23
Real Wage-Wealth 100y		-384.4* (149.9)	-3.99* (0.33)	1688.3* (0.00)	225.7* (0.00)	-3.20**
Real Wage-Wealth 20y	GREENTFP20-WPOP	560.2* (39.7)	0.81* (0.03)	199.5* (0.00)	31.4* (0.00)	-6.77*
Real Wage-Wealth 50y		1160.5* (38.2)	1.51* (0.07)	1005.6* (0.00)	49.4* (0.00)	-6.71*
Real Wage-Wealth 100y		1721.9* (152.0)	1.81* (0.63)	582.3* (0.00)	1.62 (0.20)	-0.73
Real Wage-Wealth 20y	GSTFP20-WPOP	540.2* (39.7)	0.71* (0.03)	204.7* (0.00)	84.5* (0.00)	-6.59*
Real Wage-Wealth 50y		1124.5* (37.4)	1.43* (0.07)	1003.4* (0.00)	41.7* (0.00)	-6.61*
Real Wage-Wealth 100y		1838.7* (141.5)	2.41* (0.60)	613.7* (0.00)	5.52* (0.00)	-1.42

The dependent variable is based upon: $PV\Delta C_{it} + PV(\Delta\gamma_{it}\omega_{it})$ from Equation 3, for 20-100y (years) well-being horizons. Independent: WPOP is a wealth dilution adjustment defined as the product of population growth rate and wealth per capita.

See Table 2 notes for explanations of null/alternative hypotheses and levels of significance.

Figures

Figure 1: Trend TFP growth rate, 1766-2020 (% per annum)



Notes: for sources and methods see Data Appendix

Figure 2: Five alternative investment series as % of GDP

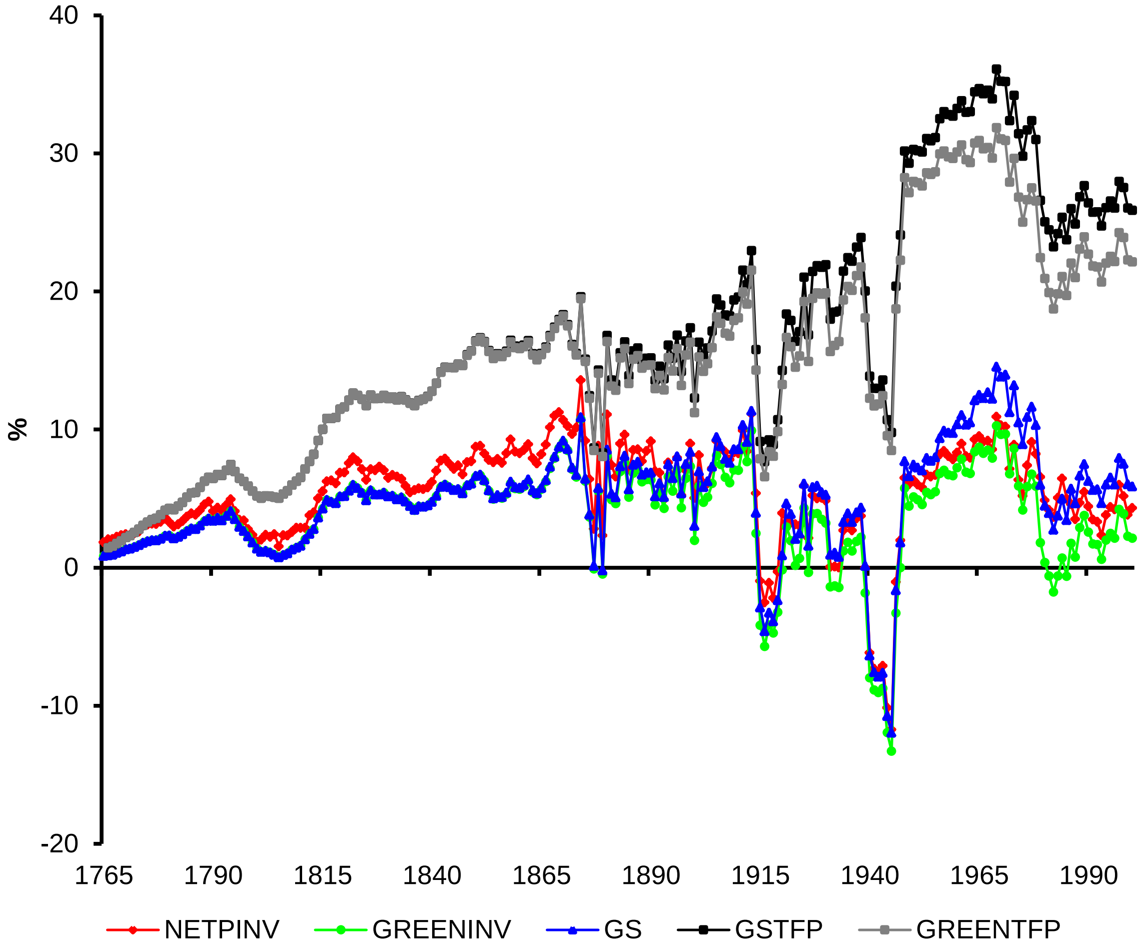


Figure 3: Five investment series per capital (£, 2000 prices)

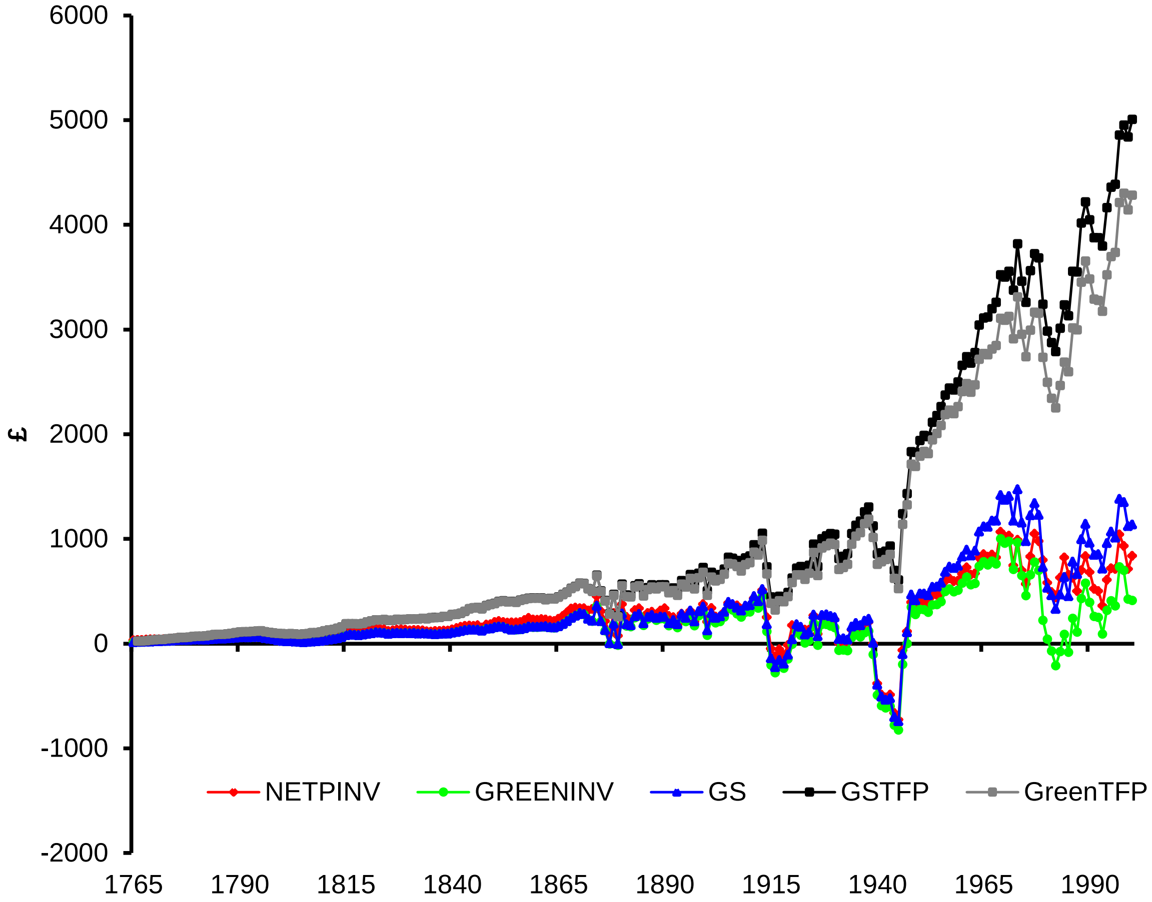


Figure 4: Genuine Savings per capita adjusted for Wealth Dilution (£, 2000 prices)

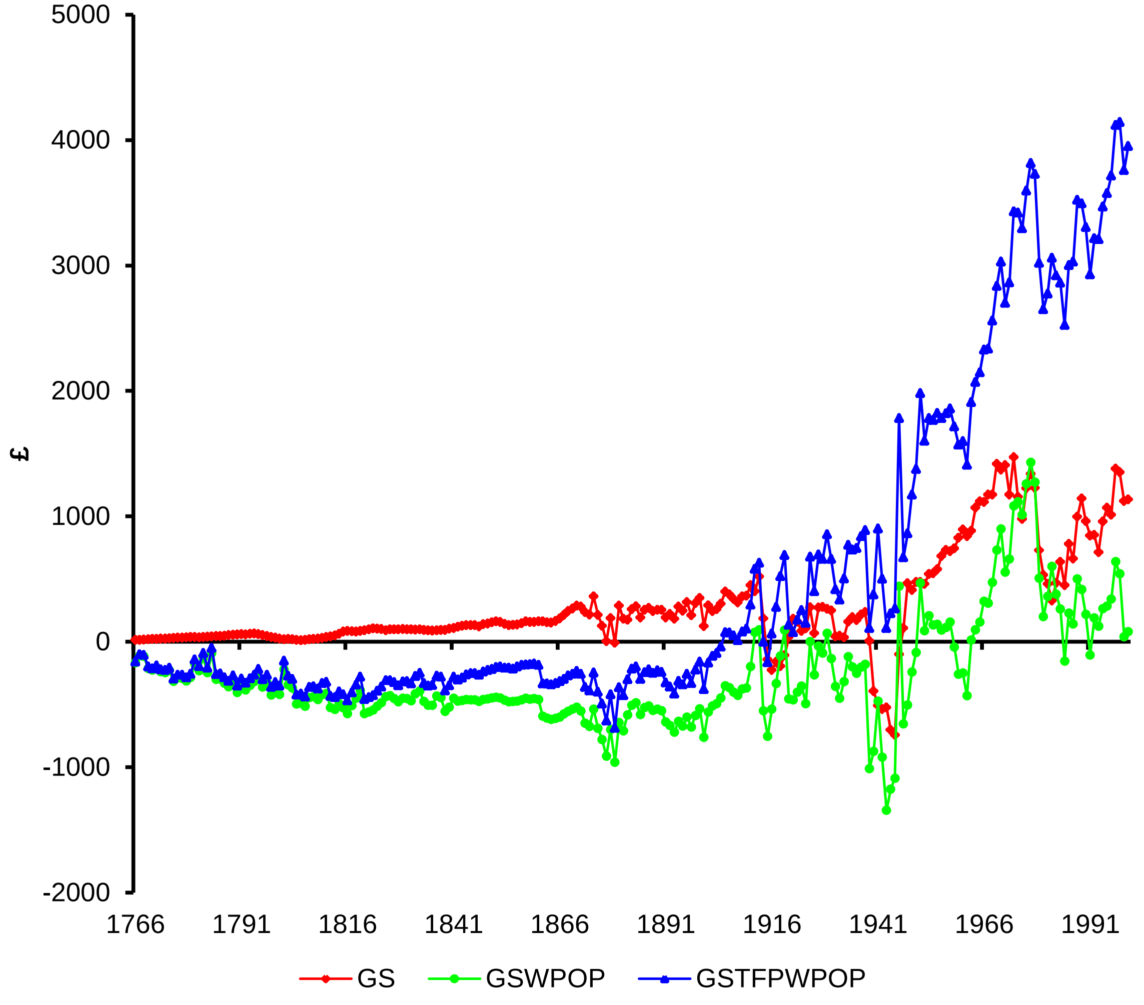


Figure 5: Present value of future changes in real wages

2.5% per annum discount rate (£, 2000 prices)