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Augmenting the World Bank's estimates: Ireland's Genuine Savings through boom and bust

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Luke McGrath, Stephen Hynes and John McHale

Abstract

The World Bank computes estimates of Genuine Savings (GS), a leading indicator of sustainable development, for most countries. A well-established literature has called for methodological enhancement. This paper presents augmented estimates of Irish GS throughout a period of unprecedented economic expansion and decline (1990 - 2016). A time-series constructed predominantly from national sources includes the most comprehensive coverage of pollutants in the literature surveyed. We apply a novel method to aid the property rights designation assessment required for transboundary pollutant accounting. In sharp contrast to the World Bank's estimates, our findings suggest that a modern developed economy can exhibit signs of unsustainability. Furthermore, extended environmental damages drive these results suggesting expanded country specific GS may diverge considerably from the World Bank's estimates. We find rapid economic development and rapid declines in environmental damages can occur concurrently and on the transition away from an unsustainable path.

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1. Introduction

Genuine savings (GS) is considered a leading economic indicator of sustainable development (Dietz and Neumayer, 2006; Hanley et al., 2015).[1] GS represents a 'balance sheet or wealth accounts' approach to natural capital accounting (UN SEEA-EEA, 2014).[2] Economic theory conceptualises sustainable development as the maintenance of an economy's comprehensive wealth through time (Neumayer, 2013). Comprehensive wealth equates the sum of the broadly defined capital stock inclusive of natural, human-made (physical), human, social and institutional capital each evaluated at their correct shadow prices (Dasgupta and Mäler, 2000; Arrow et al., 2012).[3] A consensus emerged among economists that the achievement of sustainable development entails wealth maintenance, but the debate on the conditions required continues (Neumayer, 2013).

The literature also distinguishes between 'weak' and 'strong' sustainability. Weak sustainability requires non-declining *total* wealth as all capital forms are assumed sufficiently substitutable with each other or that technological progression makes substiution a moot point. Historically, economists have postulated substitution with physical capital and technological advancement compensating for natural capital depletion (Hayek, 1941, pg. 88, 1960; Solow, 1986). Proponents of strong sustainability argue the maintenance of natural wealth is paramount as natural capital is judged un-substitutable (Costanza et al., 1991; Daly, 1991; Victor et al., 1994; Cabeza-Gutés, 1996). Empirical applications of GS are generally assumed as measures of weak sustainability. It must be stressed weak sustainability does not necessarily imply costless or inexpensive substitution in theory. For critical natural capital, for example, marginal utility to consumers and marginal rates of substitution in production tend to infinity when approaching critical levels Pearce and Atkinson, 1998).[4] Fenichel and Abbott (2014) illustrate how appropriate shadow prices could potentially represent any degree of substitutability.

GS measures net investments, the changes in the economy's comprehensive wealth. Net investments affect future well-being, negative net investments signal unsustainability through declining productive capacity and thus a declining ability for well-being generation.[5] The World Bank provides estimates of GS termed 'adjusted net savings' (ANS)

[1] GS also referred to as 'adjusted net savings' (World Bank, 2018), 'net investment' (Dasgupta and Mäler, 2000) and 'comprehensive investment' (Arrow et al. 2012). For the purposes of this paper the terms are interchangeable.
[2] Natural capital accounting is an umbrella term capturing developments in the 'green' accounting literature (Science for Environment Policy, 2017).
[3] Institutional and social capital represent key components, but data limitations mean the literature focuses on the other assets.
[4] Critical natural capital refers to any asset within the overall natural capital stock that must be maintained to preserve welfare. Pearce et al., (1989) identify the assimilative capacity of the environment (which functions to dissipate ultimately life-threatening pollutants) and some stock of living natural resources that provide basic life-support functions as "critical".
[5] This theoretical result holds under stationary technology and constant terms of trade as well as sub-optimal economies utilising the appropriate shadow prices (see the review by Hanley et. al 2015).

as well as wealth accounts for most countries in the world (World Bank, 2006, 2011, & 2018). The World Bank's focus is comparability and consistency thus trading-off against country-specific factors and national data sources. A well-established literature critically appraising the World Bank's methods calls for methodological enhancements (see e.g. Ferreira & Vincent 2005; Pillarisetti 2005; Dietz & Neumayer 2006; Atkinson & Hamilton 2007; Neumayer 2013; Boos 2015; Hanley et al. 2015).

This paper presents augmented estimates of Irish GS and provides a blueprint for other country-specific GS studies. Studying Ireland allows us to explore the effects of rapid economic convergence within the GS framework. Ireland, a European economic laggard from the 1920s (Lee, 1989), within a decade appeared to become the pinnacle of successful development. Questions surrounding the impact of such rapid economic growth on environmental quality and sustainability more generally were raised (Pepper, 1999; Clinch, 2001).[6] The World Bank ANS indicator has been repeatedly criticised, among other things, for a failure to comprehensively account for pollutants and for a reliance on highly aggregated international data. Freed from the constraint of applying a common methodology to a large sample of countries we analyse the impact of addressing these two common criticisms. We extend the pollution coverage and construct the indicator using national data sources and considering country-specific factors where possible. Ferreira and Moro (2011) (F&M hereafter) offer the sole refinement for Irish GS, covering 1995–2005, and found substantially lower savings than the World Bank. The importance of revised and expanded Irish GS is apparent due to modern data developments permitting an augmented analysis over a time period more than twice that attainable by F&M.[7]

The World Bank's ANS dataset shows persistently positive savings for Ireland and other developed economies but fails to capture important air pollutants (Clinch et al., 2006). With this in mind, we add to the existing literature by extending environmental degradation estimates to include a range of country-specific damage costs for sulphur dioxide (SO_2), nitrogen oxides (NOx), ammonia (NH_3), non-metallic volatile organic compounds (NMVOC) as well as particulate matter less than 2.5 μm in diameter (PM2.5) and a range of global damage costs for carbon dioxide (CO_2), carbon monoxide (CO) and methane (CH4). This is the most comprehensive coverage of pollutants across the literature surveyed. Another key issue for empirical applications of GS surrounds the transboundary nature of some pollutants. Two methods present themselves (Dasgupta et al., 1995). Method A, utilised by the World Bank, adopts the 'polluter pays principle' recognising the global commons as every country's asset. Method B, employed by Arrow et al. (2012), assumes

[6] Real Gross National Income grew at an average annual rate of 8% from 1994-2000.
[7] Revision is also motivated by significant modifications to the World Bank's methods since the publication of F&M as well as errors in F&M's approach found by Edens (2013).

property rights lie with the polluter. GS studies tend to utilise one of these two methods. Atkinson and Hamilton (2007) suggest presenting both methods as there is no 'correct' method rather the researcher must make a value judgement on the relevant property rights in each case.[8] We contribute to the literature by estimating damages from CO_2 and CH_4 using both accounting approaches and by applying a novel method, applicable to most other countries, to aid in the assessment of the relevant property rights designation. By capturing country-specific natural capital factors this paper offers the most comprehensive estimates of peat depletion in the literature, includes the positive impact of forestry growth and includes changes in agricultural land value.[9] Finally, we estimate human capital accumulation using the traditional expenditure method and by refining the returns to education method developed by F&M. In sharp contrast to the World Bank's estimates, our findings suggest that a modern developed economy can exhibit signs of unsustainability. Furthermore, extended environmental damages drive these results suggesting expanded country specific GS may diverge considerably from the World Bank's estimates. We find rapid economic development and rapid declines in environmental damages can occur concurrently and on the transition away from an unsustainable path. The remainder of the paper is structured as follows: Section 2 presents the theoretical framework. In Section 3 we describe the methodology detailing the adjustments to the Irish national accounts. We present our results in Section 4, compare with the existing literature and perform a sensitivity analysis. Section 5 contains our concluding remarks.

2. Theoretical Framework

The theoretical foundations of GS and the weak sustainability model trace back to the presentation of the Dasgupta-Heal-Solow-Stiglitz (DHSS) model[10] as well as the seminal contributions of Weitzman (1976), Hartwick (1977) and Solow (1986). Pearce and Atkinson (1993) calculated the first empirical estimates of GS before Hamilton (1994) and Hamilton and Clemens (1999) provided the formal theory. Well-being is at the heart of economics and ultimately satisfied by consumption.[11] This naturally led the DHSS economists to analyse requirements for non-declining consumption (or utility) through time. This is now what economists generally mean by 'sustainable development' (Neumayer, 2013). Hartwick

[8] A succinct summary of the implications of each method is provided by Hamilton (2012) a response to Arrow et al., (2012).

[9] The World Bank excludes peat depletion, agricultural land value and forestry growth. F&M include peat depletion from 1995-2005. However, F&M utilise Bord Na Mona annual reports beginning in 2002/2003 to compute estimates. Data for previous years are imputed by OLS regression. Peat data in this paper comes directly from Bord Na Mona's accounts.

[10] Dasgupta-Heal-Solow-Stiglitz, the authors contributing to the 1974 seminar on exhaustible resources in the Review of Economic Studies (Dasgupta and Heal 1974, Solow 1974, Stiglitz 1974a,b)

[11] Consumption – a broad concept in economic theory often mischaracterised as mere material satisfaction – is a bundle of all "things" that provide satisfaction and can include environmental amenities.

(1977) set out a sustainability rule requiring the re-investment of 'rent' earned from non-renewables into reproducible capital to keep the total aggregate capital stock at least constant. [12] From these foundations the green accounting literature established the comprehensive wealth (the total aggregate capital stock) of an economy, *W*, at time *t* can be represented by the sum of its assets - the stocks of human-made (*K*), human (*H*) and natural capital (*S*), evaluated at their correct shadow prices (k_t, μ_t, λ_t) reflecting their marginal contributions to utility (Dasgupta and Mäler, 2000; Arrow et al., 2012).

$$W_t = k_t K_t + \mu_t H_t + \lambda_t S_t \qquad (1)$$

A clear link exists between changes in wealth and changes in well-being providing an avenue for sustainability measurement. With constant population, stationary exogenous total factor productivity and import/export prices the change in wealth i.e. GS equates the change in well-being, expressed using a Ramsey-Koopmans formulation $V_t = \int_0^\infty U(C_\tau) e^{-\delta(\tau-t)}\, d\tau$ (Dasgupta, 2009).

$$\frac{dV_t}{dt} = GS_t = \frac{k_t dK_t}{dt} + \frac{\mu_t dH_t}{dt} + \frac{\lambda_t dS_t}{dt} \qquad (2)$$

From Eq. (2) changes in wealth (GS) have the same corresponding sign as the change in intergenerational well-being. However, GS is a one-sided sustainability indicator, negative GS implies unsustainable development although the opposite is not true. Positive GS implies a welfare improvement but cannot guarantee long-term sustainable development as an assessment of the entire equilibrium path would be required. The World Bank provides an empirical application of GS for most countries in the world termed 'adjusted net savings' (ANS) as well as wealth accounts for most countries in the world (World Bank, 2006, 2011, & 2018). The ANS indicator is largely based on Hamilton and Clemens (1999) who derived a simple model of GS and provided the equation for real-world application as:

$$GS = GNS - D_K - D_S - D_E + A_H \qquad (3)$$

Starting from Gross National Savings (GNS) as reported in the system of national accounts (SNA) deductions are made for the depreciation of the physical capital stock (D_K), the depletion of the natural capital stock which consists of sub-soil assets (D_S) and environmental degradation (D_E) and the addition of human capital accumulation (A_H). [13] Environmental degradation should include stock pollutants such as greenhouse gases (GHGs) as well as

[12] Rent is defined along paths maximizing returns to owners of the resource stock. Hartwick's rule should be paralleled with Weitzman (1976) who showed that under certain conditions accurately measured Net National Product (NNP) is the stationary equivalent of future consumption. Consequently, an augmented (green) NNP could act as a predictor of the maximum sustainable consumption level over time offering an alternative approach to sustainability measurement (see Hanley et al. 2015 for a review).
[13] A formal derivation of the GS model can be found in Hamilton and Clemens (1999)

pollutants that affect other capital stocks (see 3.3). Due to data limitations the ANS indicator includes only CO_2 and PM2.5. Human capital accumulation is roughly proxied using education spending. The following section describes the data and methods to estimate each term in equation 3. Table A1 in Appendix A summarises the data sources employed for the calculations.

3. Methodology

3.1 Gross National Savings (GNS) and Depreciation of Physical Capital (D_K)

Gross National Savings (GNS) and Consumption of fixed capital (D_K) are taken from the Irish national accounts. GNS equates GNI plus net current transfers minus total (private + public) consumption.[14] GNS minus D_K equates Net National Savings (NNS).

3.2 Depreciation of Natural Capital - Sub-Soil Assets (D_S)

For our estimates of GS from 1990 to 2016 sub-soil assets include minerals (lead, zinc, and silver), energy resources (peat, coal and natural gas) and forestry. Given the importance of agriculture to the Irish economy we also include changes in agricultural land value but in a separate analysis, in Section 4, for comparative purposes given neither the World Bank nor F&M include these values. To compute the mineral and energy depletion estimates we apply the simple net present value method (SNPVM) (El Serafy, 1989). Due to data limitations, much of the GS literature has followed the net price method which fails to appreciate remaining reserves as time passes, requires a strong assumption of optimal management (Perrings and Vincent, 2003) and has been shown to cause overestimation of depletion values (Neumayer, 2000). The SNPVM offers substantial improvements by requiring less stringent assumptions and implicitly accounts for the appreciation of reserves but does require knowledge of the lifetime of the resource and the choice of an appropriate discount rate.[15]

[14] In 1995 a major revision to the Irish national accounts occurred. Consequently, two sets of accounts exist, the 'historical' 1970-1995 series and the 'modern' 1995-2016 series, with two overlapping sets of 1995 estimates. Historical series available: http://www.cso.ie/px/pxeirestat/statire/SelectTable/Omrade0.asp?Planguage=0 Modern series available: http://www.cso.ie/en/releasesandpublications/in/nie/informationnotice-nationalincomeandexpenditure2016annualresults/ The 'historical' series differs due to the treatment of Financial Intermediation Services Indirectly Measured (FISIM). To deal with the inconsistency we take the 'modern' 1995 figure as being correct and grow back all the items in 'disagreement' for 1995 using the old growth rates to knit together a consistent series. Not adjusting the historic series risks biasing GNS and hence GS downwards. It is likely the contribution of FISIM in Ireland grew from 1990-1995 thus likely overestimating GNS.

[15] Ireland's public spending code recommends a test discount rate of 5%. A rate of 4% is employed by the World Bank and F&M thus for comparison we adopt 4% as the discount rate in section 4. We also test discount rates of 2% and 6%.

F&M utilised the SNPVM to refine the World Bank's NPM based estimates. The World Bank has since updated its depletion methodology toward a country-specific present value approach.[16] World Bank (2018) offers a substantial improvement but still relies heavily on international databases which often lack information for Ireland or differ from official sources.[17] We discuss the improvements made by the World Bank in Section 4.2.

The calculation for forestry differs as it is a renewable resource. Historically, human activity and climate deterioration caused the near complete deforestation of Ireland (O'Carroll, 2004). Forestry represented less than 2% of land cover from the mid-1800's to the mid-1900's (DAFM, 2016). Modern Irish forestry policy resulted in land cover growing to 10.5% by 2015 (CSO, 2017) and it is forecast to reach 18% by 2020 (DAFM, 2016). Although various GS studies account for positive changes in forestry stocks (e.g. Mota et al., 2010; Greasley et al., 2014; Qasim et al., 2018) the World Bank continues to make a one-sided adjustment of production above natural regeneration multiplied by unit rents.[18] F&M also omit the value of forestry growth arguing use value is non-existent due to immature timber production and that the Irish public are opposed to afforestation, citing Clinch and Murphy (2001) who examined public preferences for and against afforestation. Clinch & Murphy found the positive willingness to pay (WTP) for afforestation was outweighed by negative WTP. We include forestry growth for several reasons. In terms of the theoretical basis of GS we are interested in net investments and therefore should not include values for current public disutility or utility from increased forest stocks; this would instead be appropriate for the computation of Green NNI.[19] While Irish forestry is not commercially viable on a large scale it is government policy to achieve this (Hayes, 2014). Furthermore, a failure to account for an expanded forestry stock could be problematic for future GS calculations. In the worst possible situation, future rents from forest depletion could end up being subtracted twice without having first accounted for the stock growth (Boos, 2015). We obtain monetary values for forestry growth by multiplying the annual increase in the timber stock by the unit rent.

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[16] Calculating depletion as the ratio of the present value of rents, discounted at 4%, to the exhaustion time of the resource. World Bank (2011) limited the lifetimes of all resources to 25 years then World Bank (2018) attempted country specific estimates See https://datacatalog.worldbank.org/dataset/adjusted-net-savings for detailed methodology.

[17] For example, the proven reserves of natural gas contained in World Bank (2018) come from British Petroleum's 2018 statistical review of world energy dataset and does not contain an Ireland specific estimate.

[18] The World Bank argues merchantable timber may only represent as much as a third in net-growth countries.

[19] It is also worth noting Clinch & Murphy's survey took place during proposed afforestation policy debate with fear surrounding negative impacts of conifers a key issue (Pfeifer, 1998 as cited in Vitkova et al. 2013; Ní Dhubháin 2003). The estimates may reflect dissatisfaction with the proposed policy. Furthermore, Clinch &. Murphy (2001) warn negative WTP figures "are based on a much smaller sample and are less precise". The sample size exhibiting a positive WTP was five-fold larger. Afforestation policy has adapted considerably following Clinch & Murphy's findings reflecting the public preference for increased broadleaf species relative to conifers (Clinch, 1999, O'Leary et al., 2000, Ní Dhubháin et al., 2009). Upton et al. (2012) finds 'the Irish public holds strong, positive views for afforestation.'

Finally, we construct GS estimates from 1990-2016 to include changes in agricultural land value as this constitutes a considerable portion of Ireland's natural wealth but is not included in existing estimates of GS. We first construct estimates of the stock value by dividing land into cropland and pastureland and then estimating the annual flow of rents that the land generates and take the present value of these rents into the future following World Bank (2018).[20] The relevant values for inclusion in our GS estimates are the change in the stock value each year (which can be negative or positive). We provide more detailed methods in Appendix B for each of the components of D_S including agricultural land value.

A considerable limitation is our inability to capture non-use values (e.g. bequest and existence) and non-marketed direct (e.g. recreational and amenity) and indirect (e.g. ecosystem service benefits) use values. For some marketed resources like natural gas, this is unlikely to pose a substantial problem given the more sophisticated and competitive markets governing extraction and given the demonstrated substitution possibilities between energy and physical capital in the Irish manufacturing sector (Haller and Hyland, 2014) but may be substantial for others like forests, peatlands and agricultural land. Suffice it to say, incorporating these non-market values into GS is a complex procedure lacking consensus. Atkinson (2012) discusses the literature on forest wealth accounts and demonstrates how some of these values could potentially be included in GS. Our estimates are likely to underestimate the value of forestry growth and understate the depreciation of peat. However, it should be noted previous Irish GS estimates (World Bank, 2018; F&M) omit agricultural land and forestry growth altogether and although F&M include estimates for peat depletion the authors rely on a high degree of imputation (further discussion below).

3.3 Depreciation of Natural Capital - Environmental degradation (D_E)

A comprehensive measure of sustainability requires the capture of as broad a range of assets as feasible, including assets with negative shadow prices such as the stock of pollution (Atkinson and Hamilton, 2007). Pollution damages can be viewed as negative natural capital with emissions reductions symbolising positive investments in natural capital (Nordhaus, 2008). Damages are estimated at society's marginal willingness to pay (WTP) to reduce emissions and should reflect the present value of future impacts (Hamilton and Clemens, 1999; Dasgupta, 2001; Atkinson and Hamilton, 2007). One must exhibit caution in determining the relevant pollutants to include in GS. Changes in productive capacity are the

[20] The World Bank computes point estimates over five-year periods for the stock value of agricultural land from 1995. World Bank (2018) explains that changes in agricultural land value are not included in the ANS indicator due to data limitations.

focal point of GS thus it is easy to imagine stock pollutants (e.g. greenhouse gases) that cause damage by accumulating in the atmosphere being included in GS. Non-stock pollutants that damage other productive stocks (e.g. PM affecting human capital through increased morbidity and mortality) should also be included (Hamilton and Atkinson, 1996; Pearce and Atkinson, 1998; Atkinson and Hamilton, 2007). Another class of pollutants, "pure flow" pollutants do not accumulate in the atmosphere nor do they affect the productive capacity of the economy. Pure flow pollutants instead reduce the current utility of those directly affected, but this damage (generally) ceases with exposure (e.g. noise pollution or odour). Pezzey (2004) shows the conceptual difference between GS and Green NNI as the effects of current period economic activity on utility and thus implies "pure flow" pollutants should be included in measures of Green NNI but not GS.

The World Bank ANS indicator includes damages from the stock pollutant carbon dioxide (CO_2) and the non-stock pollutant particulate matter (PM). A well-established literature critically appraising the World Bank's calculations has repeatedly highlighted the need to expand the coverage of pollutants (Ferreira & Vincent, 2005; Pillarisetti, 2005; Dietz & Neumayer, 2006; Atkinson and Hamilton, 2007; Neumayer, 2013; Boos, 2015; Hanley et al., 2015). We include country-specific damage costs for PM, sulphur dioxide (SO_2), nitrogen oxide (NOx), non-metallic volatile organic compounds (NMVOC) and ammonia (NH_3) as well as global social costs for CO_2, carbon monoxide (CO) and methane (CH_4). In our GS calculations we include a number of non-greenhouse gases (PM2.5, SO_2, CO NOx, NH3 & NMVOC). We argue these pollutants cannot be considered as "pure flow" pollutants due to their effects on other productive stocks and/or because of their role as indirect GHGs.[21] The marginal damages we employ are largely attributable to health impacts (discussed below) and thus largely (negatively) affect the human capital stock.[22] Hamilton and Atkinson (1996) provide the theoretical foundation for the inclusion of non-stock pollutants within the GS framework and empirical applications including some non-stock pollutants have been undertaken (e.g. Hamilton and Atkinson 1996; Atkinson and Hamilton, 2007; Lindmark and Acar, 2013).[23]

[21] SO_2, CO, NOx & NMVOC are considered indirect GHGs by the UNFCCC. Other authors have assumed these pollutants affect only current utility and thus represent "pure flow" pollutants (e.g Mota and Domingos, 2013; Pezzey et al. 2006).

[22] NOx contributes to acidification and eutrophication of waters and soils and to the formation of PM and O3. Emissions of NOx adversely affect health through inflammation and reduced lung function. SO2 contributes to acidification and can affect airway function and the respiratory tract and contributes to the formation of PM. NH3 contributes to both eutrophication and acidification. NMVOCs, are important O3 precursors, certain NMVOC species, such as benzene are directly hazardous to human health. PM penetrates into sensitive regions of the respiratory system, and can cause cardiovascular and lung diseases and cancers. Primary PM is the fraction of PM that is emitted directly into the atmosphere, whereas secondary PM forms in the atmosphere following the release of precursor gases (mainly SO2, NOX, NH3 and some NMVOCs)

[23] One must be careful to mitigate the potential problem of double counting the pollution damages to the stocks of human and physical capital. Lindmark and Acar (2013) provide an excellent discussion on the issue of potential double counting. In short, one could argue that, if the human capital stock is calculated as the present value of

Emissions data is available for each pollutant from official Irish sources back to 1990.[24] Given the uncertainty and diverse range of marginal damage estimates in the literature we follow the advice of Atkinson and Hamilton (2007) and present a range of estimates. We construct three baseline measures of GS; GS1, GS2, and GS3 ranging from the largest damage cost estimates in GS1 to the smallest in GS3. All other GS components are common across the estimates. For SO_2, NOx, NMVOC, NH_3, PM2.5 a range of Ireland specific damage costs are provided by EEA (2014) and a single estimate by EnvEcon (2015). EEA (2014) assesses damages caused by air pollution by industrial facilities in the EU, Norway, and Switzerland by quantifying the health effects of primary PM as well as SO_2, NOx, NH3 and NMVOCs resulting from the formation of secondary PM and ozone through chemical reactions in the atmosphere. EEA (2014) also incorporates damages by the main air pollutants to crop and building material damage.[25] Env-Econ (2015) is a guidebook designed to provide a clear and accessible reference manual for the incorporation of marginal damages caused by air pollution in Ireland into government assessments and evaluations. EnvEcon (2015) follows a similar approach to EEA (2014). Table 1 demonstrates the marginal damage values utilised in each GS scenario and illustrates the large disparity across the two studies. The sizeable differences in the estimates reflect the different methods and assumptions used in the models to make the calculations. EnvEcon estimates are consistently lower than EEA (2014). This is likely a result of EEA (2014) containing an upper and lower bound range of estimates incorporating a more diverse set of scenarios and a more comprehensive coverage of pollutants contained in the wider analysis.[26] EEA (2014) provides a lower bound estimate obtained using the value of a life year (VOLY), and an upper-bound estimate using the value of statistical life (VSL). In this paper, GS1 takes the upper-bound estimate from EEA (2014) for each pollutant and GS2 takes the lower-bound estimate. GS3 takes the Env-Econ estimates.

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expected future income, the negative impacts of air pollution should be captured through declining wages (reflecting these damages to human capital). Although, this is further complicated when one considers that wages are determined by productivity, which in turn is impacted by technological developments (which ultimately depends on the level of human capital). Lindmark and Acar argue the potential double counting issue is abated by employing the education spending method that considers human capital as an intangible capital stock emanating from investments in formal education. Similarly, pollution damages to the productivity of physical capital should be reflected in physical capital depreciation. In this study, we assume the physical capital depreciation component fails to reflect depreciation caused by pollution as, in practice, the SNA will not capture these damages (Atkinson & Hamilton, 2007).

[24] EPA (2018), CSO (2018) and the UNFCCC data inventory.

[25] GS is interested in asset declines thus there is a strong argument that damages to crops should be removed from the analysis if soil damages affect only current output although the analysis is less straightforward if damages affect future output. It is not easy to exclude the crop damages from the damage estimates thus we include them in our analysis however it should be noted that the damage costs are likely to be underestimated as negative impacts on ecosystem services are unquantified and that the damages to crops and buildings is very small for Ireland. Env-Econ (2015) notes 95% of the marginal damages are a result of health impacts. Depreciation effects (e.g. acid rain damaging buildings and machinery), should be captured but in practice, the SNA is not sophisticated enough (Atkinson and Hamilton, 2007). In these scenarios asset value declines should be also be costed.

[26] For example, EnvEcon (2015) did not include PM10, Benzene, Polycyclic Aromatic Hydrocarbons (PAHs), Dioxins and Furans, Mercury, Lead, Nickel, Chromium, Cadmium and Arsenic in the analysis.

Both the EnvEcon and EEA studies report damages in base year euros, we assume a constant marginal damage function as no consensus on the correct deflation method exists and the inherent difficulties working with index numbers (Lindmark & Acar, 2013). We deflate the base year prices using the implicit GNI deflator. We relax the assumption of constant damage costs in the sensitivity analysis (Section 4.1) by deflating with a wage index and although this impacts the beginning of the period the underlying analysis remains unchanged. For CO_2 we do not assume constant marginal damages as it is well established how the social cost of carbon (SCC) varies with atmospheric concentrations of GHG and time. We employ a wide range of social costs for CO_2. For our headline GS estimates we convert the headline SCC estimates from Greenstone et al. (2013), which are presented in 2010 prices, to euro using OECD (2018) and then discount at 3% per annum (World Bank, 2018) for the other years.[27]

The range of carbon monoxide damages come from Shindell (2015) and Repetto et al (1997). GS1 takes the "median 3%" social cost estimate of $630/tCO (2007 dollars) from Shindell (2015), GS2 takes the "climate 3%" of $90/tCO (2007 dollars) and the GS3 estimate is $1.82/tCO (2007 dollars) from Repetto et al (1997). Costs are assumed constant, converted to euro and deflated as above. Methane damages come from Marten et al. (2015) and Waldhoff et al. (2014). The Waldhoff et al. damages are substantially lower than Marten et al. GS3 takes the lower bound estimate from Waldhoff et al of \$179/tCH_4 (2007 prices), GS2 takes the average of the baselines from the two studies i.e. \$830/tCH_4 (2007 prices) and GS1 takes the average of the upper bound estimates i.e. \$1267/tCH_4 (2007 prices). Costs are assumed constant, converted to euro and deflated as above.

Another important issue for empirical applications of GS surrounds the transboundary nature of some pollutants. The Earth's atmosphere is a global commons. When a country adds pollution to the commons how should we account for the damages? Two methods present themselves (Dasgupta et al., 1995). Method A is to employ the 'polluter pays principle,' recognising the global commons as every country's asset. The consequence is the marginal costs of a unit emitted by a country should include all costs including those accruing to other countries. In terms of a savings rule, the argument for method A is that a notional portion of national income should be set aside ready to compensate countries affected by country X's actions (Hamilton and Atkinson, 1996; Pearce and Atkinson, 1998). Holding everything else constant, a net-polluter is less sustainable due to damage liabilities (as well as damages to

[27] Greenstone et al. report a central value $21/tCO2, with sensitivity analysis to be conducted at $5, $35, and $65 (95th percentile for a 3 percent discount rate) all in 2010 prices. GS3 takes $5, GS2 takes $21 and GS1 takes $35. To obtain current market prices the discounted fixed costs in €2000 prices are deflated to current euro using the GNI deflator. The figures in dollars are converted at a constant conversion factor of 1$=1.085€ observed in 2000 available: https://data.oecd.org/conversion/exchange-rates.htm. The damages reflect a range from Fankhauser (1994, 1995), and Tol (2005,2009) and Greenstone et al. (2013) For the ANS indicator the World Bank start from a $30/t CO2 in 2015 prices and a 3% discount per annum for historic values.

itself). Method B assumes property rights to use the atmosphere as a sink lie with the polluter. Each country should then be attributed the fraction of the Earth's atmosphere reflecting that country's relative size - using some comparative metric (e.g. GDP). The savings rule for method B is for an economy to save enough, all else equal, to cover the damages that occur within its national boundaries regardless of the geographical origin of the (current) emission source giving rise to those damages. The World Bank and much of the GS literature utilise method A (Hamilton and Clemens, 1999; World Bank, 2018; Neumayer, 2013; Hanley et al., 2015). Method B is postulated by Arrow et al. (2012). There is no consensus, instead a value judgement is required on the relevant property rights in each case.[28] Hamilton and Atkinson (2007) suggest presenting both methods. We compare and discuss method A and method B in the Irish case by extending method B to include the transboundary impacts of both CO_2 and CH_4. A connected issue relates to the appropriate scale for evaluating GS and how global pollutants should be treated in this context. Our evaluation of Ireland's development path is somewhat removed from the global context. This important subject is linked with our discussion in Section 4 on "virtual sustainability". Pezzey and Burke (2014) have constructed a global estimate of GS using the World Bank ANS data comparing the "weak" ANS estimates which suggest global sustainability with "strong" indicators such as the ecological footprint which suggest the opposite. The discrepancy is resolved through the selection of carbon pricing. If CO_2 emissions are optimally controlled (globally) in the future then the ANS indicator indicates global sustainability but if uncontrolled (business as usual) unsustainability is signified. We mitigate this issue by exploring the impact of catastrophic climate change damages in the sensitivity analysis (Section 4.1).

The computation of method A is straightforward, simply multiply country X's emissions for each year by the estimated marginal damage cost. To obtain values for method B the process is more complicated. Arrow et al. (2012) take the most conservative estimate from Nordhaus and Boyer (2000) who estimate various climate change scenarios and associated impacts on the economy. The scenario corresponds to a warming of 2.5C around 2100. This level of warming is within the range projected in the IPCC's Fifth Assessment Report (IPCC, 2014). Based on this scenario, Nordhaus and Boyer (2000) estimate a 2.83% loss to OECD Europe GDP and a 1.5% loss to global GDP.[29]

To compute damages for Ireland using method B we first round the OECD Europe estimate to a 2.5% loss in GDP and take this to be Ireland's expected loss.[30] Utilising the World Development Indicators (WDI) dataset we multiply Ireland's expected loss of 2.5% by

[28] See Hamilton (2012) response to Arrow et al., (2012) for a succinct summary of the implications of both methods.
[29] The average estimated loss to global GDP from the studies contained in the IPCC report (omitting outliers) is 1.4% when restricted to the studies containing scenarios within the IPCC projected range.The outliers are Tol (2003) estimate of positive 2.3% and Maddison and Rehdanz (2011) negative 12.4%.
[30] For consistency with F&M.

Irish GDP for each year and global losses (1.5%) by global GDP for each year. This allows us to calculate the proportion of global damages suffered by Ireland in each year (ranging from 0.3-0.8%). Global monetary damages caused by both pollutants for each year are obtained by multiplying the social costs of CO_2 and CH_4, as outlined above, by world emissions taken from the WDI database.[31] Finally, we multiply these global losses for each year by the expected proportion of losses accruing to Ireland. As method A yields consistently lower total damages (and consequently higher GS estimates) it is included in the headline analysis in section 4 for conservative reasons. Method B is employed and discussed within the sensitivity analysis contained in section 4.1 where we also apply a novel method to aid in the assessment of the relevant property rights designation. Where country specific estimates of pollutants are utilised (i.e. those except CO, CH_4, and CO_2) we are accounting for damages to Ireland caused by Irish emissions. The implicit assumptions are that no damages accrue to other countries from Irish emissions and Irish emissions cause no damages to other countries

[31] World CO_2 and CH_4 emissions are reported to 2014 & 2012 respectively - remaining years estimated by linear interpolation.World emissions data for CO_2 are available up to 2015 we impute 2016 emissions by linear interpolation. Global CH_4 emissions are available up to 2013 missing years are imputed by linear interpolation.

Table 1: Marginal Damage Costs employed across each Genuine Savings scenario in year 2000 prices

Pollutants*	GS1/	GS2	GS3	Emissions 1990	Emissions 2016	% Change in Emissions 1990-2016
CO_2	€88/tC (€24/tCo2)	€51/tC (€14/tCo2)	€11/tC (€3/tCo2)	32878 kt	39928 kt	+21%
PM2.5	€32,096/t	€10,717/t	€6,371/t	35 kt	15 kt	-58%%
SO_2	€25,777/t	€8,766/t	€4,099/t	184 kt	14 kt	-93%
NOx	€7,790/t	€2,974/t	€849/t	175 kt	107 kt	-39%
NH_3	€4,008/t	€1,347/t	€701/t	110 kt	117 Kt	+6%
CO	€518/t	€74/t	€2/t	350 kt	106 kt	-70%
NMVOC	€2,107/t	€833/t	€743/t	146 kt	108 kt	-26%
CH_4	€841/t	€748/t	€156/t	595 kt	548 kt	-8%

*CO_2 =carbon dioxide; PM2.5 = particulate matter, SO_2 = sulphur dioxide, NOx = nitrogen oxides, NH_3 = ammonia, CO = carbon monoxide, NMVOC =non-metallic volatile organic compounds & CH_4 = methane.

3.4 Human capital accumulation (A_H)

Within the wealth accounting approach, human capital accumulation can be approximated using expenditures on education, as a rate of return on time spent in education, or as a measure of discounted lifetime earnings by skill level (Greasley et al, 2014). The World Bank utilise UNESCO estimates of current operating expenditure. This method implies X euro spent on educational expenditure equates to an X euro increase in human capital. The World Bank views education spending as a lower bound estimate for human capital correcting for the misallocation of investment expenditures as consumption within the SNA (Hamilton, 1994; Hamilton and Clemens, 1999). An alternative view offered is that education spending may be an overestimate due to a lack of depreciation (Dasgupta, 2001) or the ineffectiveness of public schooling (Caplan, 2018). The expenditure method has attracted much criticism (Jorgenson and Fraumeni, 1992; Schultz, 1988). F&M estimate human capital by the returns to education arguing their method is "more consistent with the current consensus in the literature." We refine the method developed in F&M and report the result in the sensitivity analysis in Section 4.1. A_H is estimated as $\Delta H_t = \mu_t(\Delta H_t/\Delta_t)$ where μ_t approximates the market returns to education.

We derive the annual value of human capital accumulation by multiplying the annual predicted earnings by educational attainment by the annual change in the labour force at each educational level.[32] With regard to human capital, immigration and emigration are implicitly captured by the annual change in the workforce at each educational level. Census data is interpolated to gain estimates of annual labour force changes at each educational level.[33] We

[32] Lower secondary, upper secondary, lower third level and higher third level.

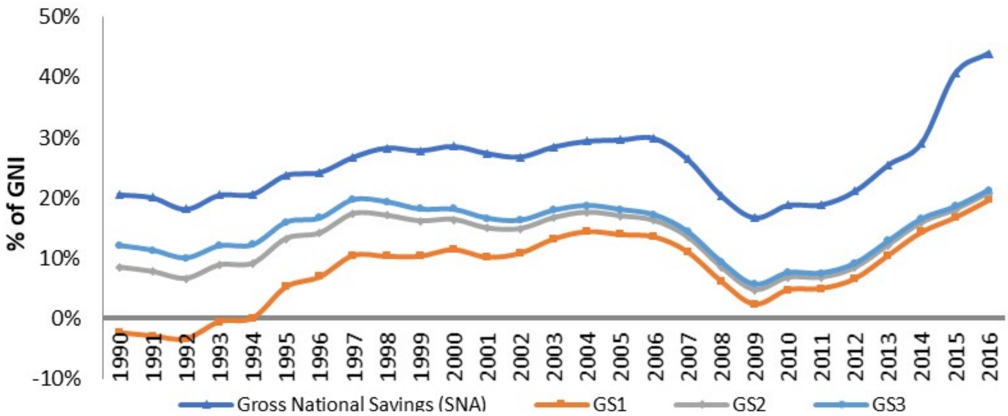
[33] Data available here https://www.cso.ie/en/census/ we use 1981; 1991; 1996; 2002; 2006; 2011; 2016 and linear interpolation.

gain estimates of predicted earnings at each education level by multiplying the estimated annual wage for those with primary education only by 1 + the coefficient on the return to education. Wages for those with primary education are reported for 2002, and 2005-09 in the CSO's Statistical Yearbooks.[34] For the missing years, we take the average proportion (94%) of the average industrial wage earned by those with primary education from observable years (2002, 2005-2009) and assume this is constant over the period.[35] The returns to education coefficient is taken from Barrett et. al (2002) as the average for years 1987, 1994 and 1997 and is assumed constant over the observed period.

4. Results

We estimate Eq. (3) for each scenario outlined in Section 3 to obtain GS for each year. GS is reported as a savings rate (proportion of GNI). Estimating sub-soil asset depletion DS requires the use of a discount rate. Ireland's public spending code recommends a test rate of 5% while a rate of 4% is employed by the World Bank and F&M. Changing the discount rate has a negligible impact on the absolute savings rates. Therefore, for ease of exposition and consistency with previous studies we report results employing a 4% discount rate (we also tested 2% and 6%). Section 3.4 outlined two methods for approximating human capital accumulation. For conservative reasons, we focus on education spending as this method yields higher GS but also discuss the returns to education method in the sensitivity analysis (Section 4.1) and in comparison with F&M in Section 4.2. Section 3.3 described two methods for the allocation of property rights for environmental degradation. Method A 'the polluter pays' principle is employed here, again for conservative reasons and as it may be more appropriate for Ireland (see Section 4.1). Finally, all figures are constant 2000 euro unless otherwise stated. All series are constructed in current prices and for consistency, deflated using the implicit GNI deflator.36 Fig. 1 illustrates our headline estimates of GS1, GS2, and GS3. Immediately we observe that neither "Celtic tiger" growth, from the mid-90s to the mid 00's, nor the economic downturn from 2008-2010, appear to coincide with unsustainable development. Pre-tiger, the Irish economy signals unsustainability through low or negative savings from 1990-1995. We find some evidence to suggest the economy transitioned away from an unsustainable path during the boom period.

[34] https://www.cso.ie/en/statistics/statisticalyearbookofireland/
[35] https://www.cso.ie/en/releasesandpublications/ep/p-hes/hes2015/aiw/
[36] Although not reported here employing CPI for deflation consistently yields lower absolute GS figures (and consequently higher negative savings at the beginning of the period under the GS1 scenario).



Note: GS1 takes the upper bound environmental damage estimates from the literature, GS3 the lowest (see 3.3). All other components are common across the estimates

Figure 1: Gross National Savings and our range of Genuine Savings estimates 1990-2016

Our findings contrast with the GS literature which consistently shows positive savings for developed countries (Pearce and Atkinson, 1993; Hamilton & Clemens, 1999; Arrow et al., 2012; World Bank, 2018). The rare observations of negative savings in developed economies has generally arrisen as a result of the Great Depression, World Wars (Blum et. al, 2017) or volatility in natural resource prices/harvest (Hanley et al., 1999). Fig. 2 provides a decomposition of GS1; evidently environmental externalities drive our observed negative savings at the start of the period. We found just one study with somewhat similar findings. Hamilton and Atkinson (1996) who add SO_2 and NOx emissions observe negative savings across the UK from 1980-1987.[37] However, Hamilton and Atkinson attribute the transition to positive savings to volatile oil prices as environmental damages fell slightly while net investments in physical capital remained stagnant. Lindmark and Acar (2013) found Sweden's transition to positive savings after 1910 to be the result of increasing pollution damages (CO_2, SO_2, NOx, PM10 and N-leakage) being more than compensated for with rising human capital accumulation, net physical capital investment and reduced sub-soil asset depletion. In comparison, our findings suggest rapid economic development *and* rapid declines in environmental damages can occur concurrently and on the transition away from an unsustainable path.

[37] The authors apply *'crude scaling'* of estimated UK damages and find negative savings for Portugal and Ireland in 1980.

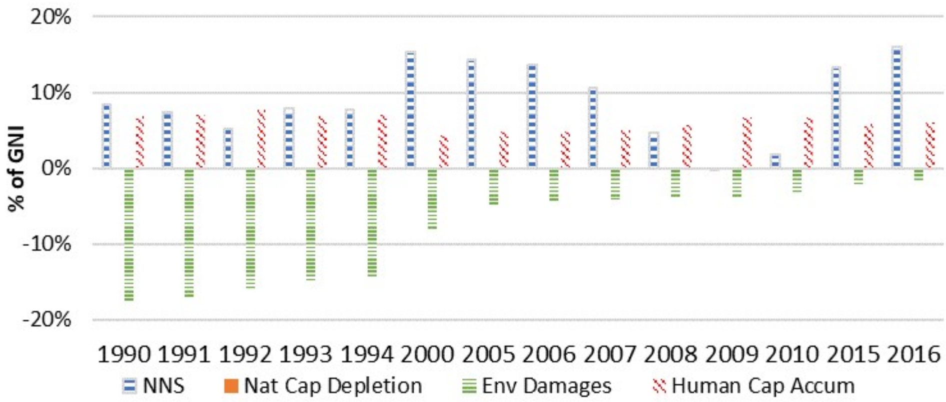


Figure 2: Breakdown of GS1 components 1990-2016 (selected years)

Ireland's savings evolve through four distinct periods. Initially, from 1990 to 1994 the economy is characterised by low economic growth, low net physical capital investment and high environmental damages. For the first five years, negative savings occur in the GS1 scenario averaging −2% of GNI. In 1994, savings are barely negative at −€60 m or −0.1% of GNI. Throughout this initial period, environmental damages of €9bn or 18% of GNI outweigh the combined net investments of physical and human capital of 15% of GNI. During 1994, we see that although GS may be positively related to conventional economic growth, 'green' adjustments can have a sizable impact. Rising consumption and depreciation coupled with rising environmental damages offset strong real GNI growth (7%). From 1995, a second period begins, a decade of strong real economic growth translating into strong positive net investments. During Ireland's rapid economic convergence real GNI doubles from €60bn in 1995 to €117bn in 2005 (8% growth per year up to 2000). Two central theories, with some obvious overlaps, offer explanations for Ireland's rapid growth. Delayed convergence due to a delayed adoption of free trade and raising of the educational quality of the workforce (O'Grada, 2002; Honohan and Walsh, 2002) or a regional boom (Krugman, 1997) fostered by foreign direct investment (largely from the US) underpinned by low corporation tax rates and membership of the EU. During the boom we observe a rapid increase in GS driven by considerable reductions in total environmental damages as well as strong net physical capital investments.

As a percentage of GNI, environmental damages are halved across all scenarios by 2000 are halved again by 2006 and once again by the end of the observed period. The level of net physical capital investment in 2003 is €15.1bn (15% of GNI), double its level in 1991. GS1 rises to 5% of GNI in 1995, GS2 increases to 13% of GNI (up from 9% GNI in 1994) and GS3 rises to 16% of GNI (12% in 1994). From 1998 to 2001 education spending falls. By 2004, GS across all scenarios was over 14% of GNI. A key criticism of the GS measure highlighted by Pillarisetti (2005) is the high correlation between GS and conventional investment (NNS). In the Irish case one might question if NNS growth was as "genuine" as the fall in environmental damages?[38] The "true" Celtic tiger arguably occurred from 1994-2001 before being replaced by a credit fuelled construction and consumption bubble (McDonnell, 2015).[39] Ireland's net investments in physical capital reflect the large and rising "dwellings" component of domestic fixed capital formation (GDFCF). From 1995 to 2000 the dwellings component of GDFCF (30–40% of the total) rose from €6bn to €10bn (constant 2015 prices). Ireland's net investments in physical capital reflect the large and rising "dwellings" component of domestic fixed capital formation (GDFCF). From 1995-2000 the dwellings component of GDFCF (30-40% of the total) rose from €6bn to €10bn (constant 2015 prices). This is unsurprising when one considers the dramatic increase in labour force participation and employment growth, particularly female participation, coupled with the reversal of historical migration patterns. However from 2001, Ireland's economic growth became reliant on a construction bubble (McDonnell, 2015). GDFCF and consequently NNS are driven by dwelling construction continuing to rise rapidly from 2001 to a high of €17bn in 2006 (40% of total GDFCF). From 2005 a third period begins, one of falling GS that lasts until 2010. Despite GNI growth averaging 5% from 2005 to 07, the GS rate fell by 3–4 percentage points across all scenarios. Reduced net physical capital investments outweighed continued declines in environmental damages. Following the housing bust and subsequent economic downturn the dwellings component of GDFCF fell sharply from 2006 to a low of €3.5bn in 2013 (a decline of 80%). From 2008 to 09 GNI growth is negative and as NNS collapse only education spending, which continues to rise in real terms during the downturn, prevent negative savings. From 2010, GS returns to the pre-crisis trend. The final period sees strong GNI growth translate into increased net physical capital investment which is far less reliant on building and construction (dwellings represent just 10% of total GDFCF). Environmental damage reductions continue and these positive factors outweigh declines in real education spending. Large increases and new peaks in GS are found across all scenarios from 2010 to 2016.

Analysing the evolution of Irish GS rates is more complicated if one considers the impact of population growth on the GS model. With a growing population, per capita wealth rather than total wealth should be sustained (Neumayer, 2013).[40] Over the period observed Irish population growth averaged 1% per annum. How to appropriately account for population

[38] Pillarisetti (2005) argues GS adds little additional value to conventional concepts but from a predictive perspective correlation is of little importance what actually matters is the slope of the regression line involving the indicator and the measure of well-being. GS is useful if it "corrects" the slope and aligns with GS theory (Hanley et al., 2015).

[39] Between 2000 and the peak of the housing boom in 2007, average house prices in Ireland doubled before subsequently returning to the level that they were at in 2000 by 2013.

[40] Arrow et al. (2003) show when population growth is exponential the sustainability criteria should be considered in per capita terms. Other growth profiles require more complex amendments. Asheim et al. (2007) show population growth must be quasi-arithmetic to be compatible with sustainability in a competitive framework. Li and Lofgren (2013) show how uncertainty regarding population growth requires a subtraction from GS a term reflecting the welfare loss from risk aversion

growth is not straightforward. A higher population increases the level of human capital available but also raises resource consumption.[41] Hamilton and Atkinson (2006) recommend dividing GS by total population, deducting a so-called Malthusian correction term that multiplies comprehensive wealth per capita by the population growth rate for per capita wealth changes. The practical difficulty in constructing this correction term lies in insufficient data on comprehensive total wealth.[42] A simplified approach is to divide total GS by population permitting preliminary GS rates per capita. Alternatively, comparison of the population growth rate with the total GS growth rate yields similar insight. We include estimates of GS per capita in Appendix A and find little evidence of a wealth dilution effect across the indictors.

Another important consideration missing from the World Bank ANS indictor is the role of technology. Technical progress can be viewed as another capital stock or the "value of time passing" and unlike population growth is unambiguously positive for sustainability. Weitzman (1997) was the first to examine technical change as a source of time dependence suggesting an upward adjustment of up to 40% of GNI for a notional economy. Many have argued for the inclusion of exogenous technological progress (using a measure of total factor productivity (TFP)) (Pemberton and Ulph, 2001; Pezzey, 2004; Pezzey et al., 2006). Arrow et al. (2012) simply add the current value of TFP to their GS measure. Others (Mota et al., 2010; Greasley et al., 2014; Hanley et al., 2015; Blum et al., 2017; Lindmark et al., 2018) have argued what should be included is the present value of future changes in TFP over 10–50 year horizons reflecting the uncertainty over the length of time the value of technological advancements persist. Byrne and McQuinn (2014) estimate that from 1987 to 1996 TFP accounted for 4.3 percentage points of Irish annual growth of 7.2% (Real GNP) before slowing to 1.1 percentage points of 4.9% annual growth from 1997 to 2006. This level of TFP growth was well ahead of any other Western European country and a simple addition to GS would eliminate the negative savings rates observed from 1990 to 1995 in our headline results. Estimating the present value of TFP leads to a much larger positive impact on Irish GS. Taking the information on trend TFP growth from Byrne and McQuinn and assuming a 10 year time horizon and assuming discount rates of 2%, 4% and 6% we find that the average annual present value of TFP is 29–40% of GNI from 1990 to 1995.[43] This magnitude of TFP eliminates negative savings even in our most pessimistic scenario contained in the sensitivity

[41] The thesis of Simon (1981) is that population growth is the "ultimate resource".
[42] This obstacle may be overcome in future given the World Bank already produce point estimates for 95, 00, 05, 10 and 15.
[43] Although not directly comparable due to differences in truncation and discounting Blum et al (2016) finds the following average annual rates of the PV of TFP from 1990-2000; Britain 23%, Germany 38%, US 24%, Australia 18%, France 27%, Switzerland 28%, Argentina 10%, Brazil 22%, Chile 5%, Columbia 2% & Mexico 7%. Greasley et al (2014) find the average annual PV of TFP to be 22% of GDP in Britain from 1950-1999. Hanley et al. (2015) find average annual rates of 26, 19, and 34% of GDP in the USA, Britain and Germany respectively from 1870–1990.

analysis (Section 4.1). However, there are a number of reasons to doubt these magnitudes of TFP. Firstly, TFP is related to innovativeness, intangible assets, institutions and social capital. Consequently, adding TFP risks significant 'double-counting' (Hamilton, 2012). Secondly, Byrne and McQuinn as well as Honohan and Walsh (2002) argue Ireland's TFP estimates are likely biased upwards due to transfer pricing by US multinationals distorting the interpretation of productivity gains. Finally, the green accounting literature argues conventional accounting aggregates are deficient for environmental policy yet the output measure employed in the calculation of TFP is conventional GDP (or GNP for Ireland) and not an alternative "Green" adjusted variant. Also, the TFP estimates do not account for "green" capital (see Mota et al., 2010 for discussion). In this regard, Vouvaki and Xepapadeas (2009) estimate that from 1965 to 1990 Ireland's average annual TFP growth was 1.6% but adjusting for environmental externalities this becomes negative at −0.17%.

The evolution of the environmental damages warrants a more detailed examination. Fig. 3 shows the range of total environmental damage costs. In GS1 damages fall from 18% of GNI (€9.5bn) to 3% (€3.9bn) over the observed period, in GS2 damages fall from 7% of GNI to 1% and in GS3 damages fall from 3% of GNI to 0.4%. There is not only a sharp decline in environmental damages but also a sharp decline in emissions, only CO_2 and NH_3 emissions are higher in 2016 than in 1990 (Table 1).

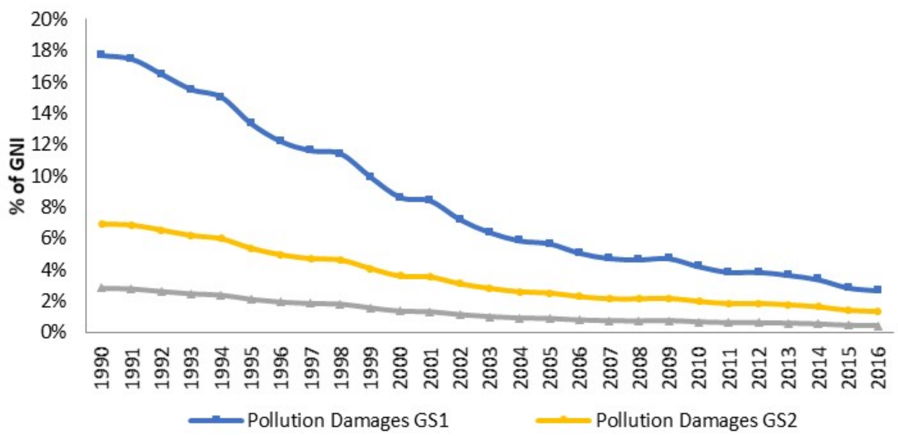


Figure 3: Total environmental damage as % of Gross National Income 1990-2016

Fig. 4 provides a breakdown of the external costs demonstrating SO_2; the largest component for almost two decades, has been the key driver of the total damage costs. SO_2 emissions have fallen 92% from 1990 due to a mixture of market-based incentives, structural changes and environmental policies. The shift to cheaper cleaner natural gas and the installation of modern technology in power stations is the most sizable driver. Ireland has been below the SO_2 National Emissions Ceiling (NEC, 2010) since 2009 (EPA, 2018).

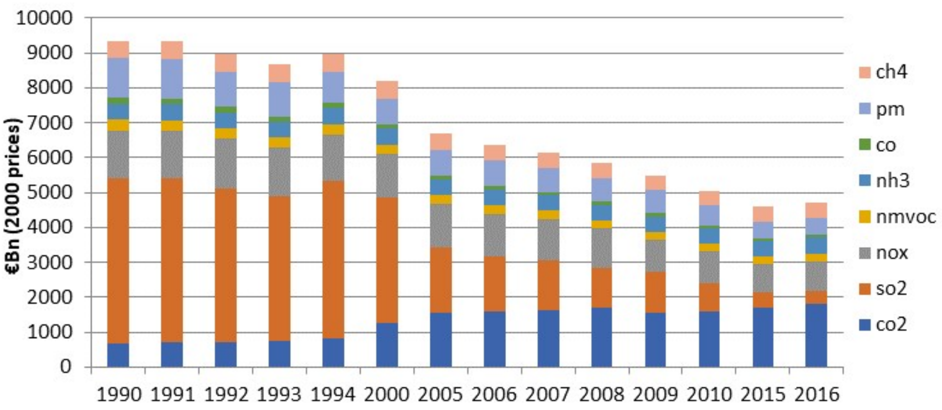


Figure 4: Breakdown of total environmental damages from GS1 scenario for selected years

NOx emissions declined 40% over the observed period. Power generation and vehicles are the primary sources of NOx emissions and modern technology and a switch to natural gas in power generation drove reductions.[44] Just two of the pollutants studied have risen across the period; CO_2 and NH_3 and are both heavily influenced by agriculture. CO_2 rose 24% but declined from a 2005 peak of 47% above 1990 levels. CO_2 overtook SO_2 as the most sizeable component of total damages since 2007 (this rests on the large marginal damage cost employed). NH_3 emissions exceeded the NEC emission ceiling in 2016 for the first time and reductions may be difficult given ambitious government targets in Food Wise 2025 (EPA, 2018). In relation to the remaining pollutants, PM damages have more than halved over the period due to reduced use of coal and peat, technological advances and the transport fleet structure (EPA, 2018). NMVOC emissions fell 27% from 1990 due to technological controls in motor vehicles along with reduced coal and peat use (EPA, 2018).[45] CH_4 damages have declined from a range of €93m-461m in 1990 to €85m-440m in 2015. Finally, CO emissions have fallen considerably but have a small impact on total damages.

Unsurprisingly for an economy with a low endowment of mineral and energy resources, adjustments for sub-soil assets have the least impact on savings rates (0.1% of GNI on average). Irish zinc accounts for a quarter of total European zinc production (Minerals Ireland, 2018) and zinc extraction and prices drive non-renewable sub-soil asset adjustments (€120m per year). Zinc extraction rose steadily from 1965 peaking at 445 thousand tonnes (kt) in 2005. Zinc production has declined since evidenced by the production of 148kt in 2016. Natural gas depletion will be a large component of sub-soil asset depletion in the future. In 2016 natural gas depletion equated the value for zinc extraction (100m). This reflects the

[44] In 2016 Ireland was 42.3kt above the 2010 NEC emission ceiling for NOx and has applied an adjustment as allowed under Article 5(1) of Directive 2016/2284 to comply..

[45] Ireland has applied an adjustment to NMVOC emission inventories, as allowed under Article 5(1) of Directive 2016/2284 in accordance with Part 4 of Annex IV to comply. NMVOC emissions are, on average, 52.8kt above the 2010 emission ceiling.,

significant increased production from the Corrib gas field which commenced production at the end of 2015.

Irish gas production averaged 40,000 terajoules (TJ) from 1990-2015, 0.5% of the EU total per year and had been in rapid decline prior to Corrib coming on stream. Production rose in 2016 to 104,000 TJ, 2.3% of total EU production representing a two thousand percent increase from 2015. As outlined earlier peat depletion and the value of forestry growth are likely to be understated and this is reflected in low estimated values. Ireland accounts for circa 15% of world peat production (USGS, 2017) and peat represents a valuable resource of historical and cultural significance (Clarke, 2010).[46] Peat depletion averages €3m per year while forestry growth adds an average of €32m per year. Peat production averaged 4.1Mt per annum over the observed period peaking at 7.4Mt in 1990. The SNPVM fails to capture the non-marketed value of peat resources. Peatlands possess a high capacity for carbon storage and provide a multitude of other non-marketed ecosystem service benefits. The lost ecosystem service benefits and other non-market values will not feature in the depreciation estimate; however, damages from the burning of peat will be implicitly captured in estimates of pollution damage.

A large literature suggests government policy in relation to peat harvesting may result in overexploitation (see for example; Nic Giolla Choille, 1992; Honohan, 1997; FitzGerald et al., 2005; Tuohy et al., 2009; Bullock and Collier, 2011; Gorecki et al., 2011; O'Mahoney et al., 2013; Farrell and Lyons, 2015; Lynch, 2017). In Ireland, the energy regulator is obliged to surcharge all electricity users through a Public Service Obligation (PSO) levy to subsidise peat-fired electricity on the grounds of energy security (CRU, 2018). Political concerns regarding employment in the Irish midlands means socio-economic policy may also be an implicit factor (Honohan, 1997; Manning and McDowell, 1984). A chief concern surrounds the decision that peat plants run at full capacity. Tuohy et al. (2009) argued security need not be sacrificed by running at a lower capacity. Furthermore, policy developments such as greater electricity interconnection may have sufficiently alleviated earlier security concerns (Gorecki et al., 2011). In relation to future policy development, it may be prudent to follow the advice of Lynch (2017) recognising various energy policy goals can conflict and the potential danger of adding additional goals on an ad-hoc basis. There is another question mark over the low depletion estimates that of “virtual sustainability” (Atkinson et al., 2012). The depletion estimates are accounted for using a production-based methodology as the conventional thought is that the liability arising from the (negative) change in the resource stock arising from depletion should be attributed to the accounts of the producing country. Atkinson et al. posit responsibility as residing with the economy ultimately consuming the

[46] https://minerals.usgs.gov/minerals/pubs/commodity/peat/mcs-2017-peat.pdf

resource.[47] Is Ireland importing its sustainability? Atkinson et al. (2012) find Ireland to hold one of the world's largest ratios of per capita consumption-based depletions to the global average. This implies production-based accounting may considerably understate the value of resources required to meet domestic demand. This is hardly surprising given Irelands high energy import dependency which in 2004 (the basis for the Atkinson et al. estimates) was 90% although this has fallen to 66% in 2017 largely due to production from Corrib reserves (SEAI, 2018).

Changes in agricultural land value are much more sizeable than energy, mineral and forest resources combined and account for adjustments of 2% of GNI on average (Fig. 5). Land value depreciates year on year from 1990 to 2006 averaging −2% of GNI and then appreciates year on year from 2007 to 2016; a positive adjustment to GS of 1% of GNI.[48] The changes in land value closely follow changes in the value of milk and cattle production. This is because pastureland accounts for 90% of total agricultural stock value and in turn is driven by milk and cattle production which together make up 85% of the value of the pastureland stock.

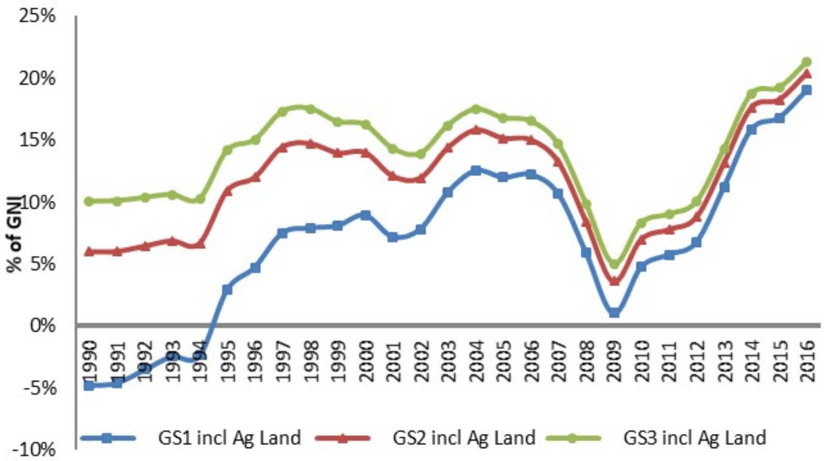


Figure 5: GS including changes in agricultural land value 1990-2016

4.1 Sensitivity Analysis

Measuring GS entails a considerable degree of uncertainty. It is therefore prudent to provide a broad range of estimates across various scenarios. Weitzman (2009) argues the evaluation of climate change policy should focus on the consequences of fat-tailed structural uncertainty along with uncertainty arising from temperature variability, i.e. high impact low probability events. This implies the 95th percentile of the probability density function should be

[47] A major issue acknowledged by the authors is that measuring resource consumption does not translate directly into an obvious rule about how much a resource-consuming economy should save to ensure its own sustainable own development.

[48] Using a 6% discount rate results in negative savings being observed in 2009 and savings rates of 0-1% in 1995 and 1996.

considered. Columns 1–3 in Table 2 include GS estimates where CO2 and CH4 damages are altered in each scenario to represent 95th percentile estimates.[49] The large damage costs do not change the underlying trends in GS but depress GS rates by 4–6 percentage points per year across the scenarios from 1990 to 1994. As the majority of emissions decline considerably over the period the depression dampens. GS1 turns negative in 2009 but as the economy returns to growth, savings rates increase year on year up to 2016. Another important issue relates to the earth's atmosphere representing a global commons. In Section 3.3 we outlined two methods of accounting for transboundary damages. Columns 4–6 in Table 2 present GS using method B to account for damages emanating from CO2 and CH4 emissions. We find that method B yields considerably higher damages for every year. This is in contrast to F&M who found method A to yield higher total damages from 1995 to 2002 and method B for the remaining years. This likely reflects the fact that F&M assumed a constant marginal damage function for CO2 emissions, updated global emissions data from the World Bank and our addition of CH4. Utilising method B pushes the savings rate down by 1–4 percentage points on average compared to the method A equivalents. The reduction results in negative savings observed from 2008 to 2010 in the GS1 scenario. Hamilton and Atkinson (2007) suggest presenting estimates from both methods of accounting as a value judgement is required on the relevant property rights in each case. We apply a novel method to aid in the assessment of the relevant property rights designation for CO2 and CH4 emissions.

Table 2: Genuine Savings sensitivity analysis 1990-2016

Year	(1) GS1: Catastrophic damages	(2) GS2: Catastrophic Damages	(3) GS3: Catastrophic damages	(4) GS1 Transboundary Method B	(5) GS2 Transboundary Method B	(6) GS3 Transboundary Method B
1990	-8%	2%	5%	-5%	7%	12%
1991	-9%	1%	4%	-6%	6%	11%
1992	-9%	0%	3%	-6%	5%	10%
1993	-6%	3%	5%	-3%	7%	12%
1994	-5%	3%	5%	-2%	7%	12%
1995	0%	7%	9%	3%	11%	16%
2000	7%	11%	12%	9%	14%	16%
2005	9%	12%	13%	8%	13%	17%
2006	9%	11%	12%	8%	12%	16%
2007	7%	9%	9%	5%	9%	13%
2008	2%	4%	4%	0%	4%	8%
2009	-2%	0%	0%	-4%	0%	5%
2010	0%	2%	2%	-1%	3%	7%

[49] \$206/tC (1995 prices) from Tol (2009) and \$3200/tCH4 (2007 prices) from Marten et al. (2015).

2015	13%	14%	14%	11%	14%	18%
2016	16%	17%	17%	14%	16%	20%

As described in Section 3.3 we make these calculations beginning from an assumption of 2.5% to be the expected loss to Irish GDP under a scenario of 2.5°C warming around 2100. The 2.5% loss is based on the average loss to OECD Europe reported in Nordhaus and Boyer (2000) but we can, in fact, construct Irish specific estimates from the existing literature. Table SM10.2 WGII of the IPCC Fifth Assessment report (IPCC, 2014) presents existing estimates of the total and marginal economic impact of climate change.[50] Some of the results are aggregated by Tol (2013) and are provided in a supplementary spreadsheet. Using Tol's aggregation methods one may construct country-specific estimates for most countries. For Ireland, we infer a GDP gain of 0.05% under a 2.5°C warming scenario from Maddison (2003). We infer a 0.17% gain to Irish GDP from Rehdanz and Maddison (2005), a scenario of 1 °C warming. Using either of these inferred estimates in the computation of method B would imply an odd scenario where Ireland should, in fact, account for gains rather than damages accruing from pollution. Given the uncertainty surrounding climate change and its global externality nature, it may be more appropriate in the Irish case to assume method A as the relevant choice of property right to construct GS.

Section 3.4 detailed two methods to account for human capital accumulation. Fig. 6 illustrates the range of GS utilising the returns to education method. On average, GS estimates are depressed by 4 percentage points. The trend remains but the depressed savings push GS down to 0.03% of GNI in 1995. GS also turns negative in 2009, 2010 and 2011 in the GS1 scenario, and 2009 in the GS2 scenario. Savings rates across all scenarios return to double digits by 2015.

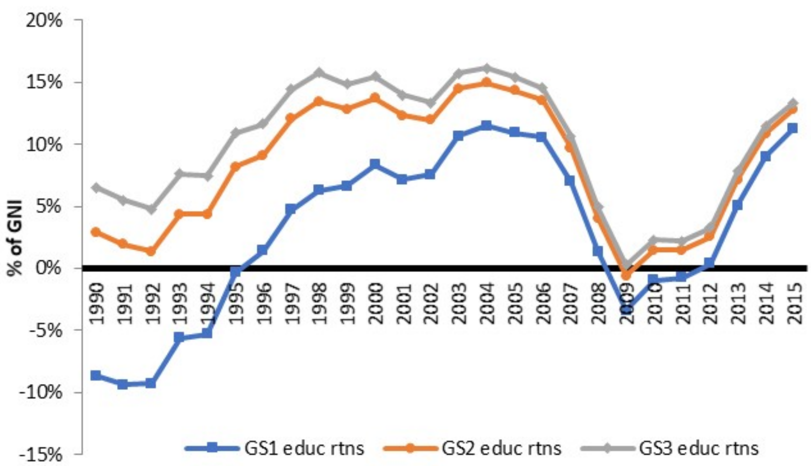


Figure 6: Range of Genuine Savings estimates employing returns to education 1990-2015

[50] https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/supplementary/WGIIAR5-Chap10_OLSM.pdf

Finally, apart from CO2 the marginal damage function was assumed constant for the pollutants that yield the above results. Although GS studies have assumed constant marginal damages (Mota et al., 2010; Ferreira and Moro, 2011) this is likely to bias the pollution damages upwards for Ireland given the substantial change in economic activity over the period. The marginal damage values are largely based on damages to human health thus we relax the constant damage assumption for the main air pollutants (SO2, NOX, NMVOC, NH3 and PM2.5) by deflating the fixed damage costs using a wage index constructed from the real average industrial wage from the Irish CSO. Even accounting for a non-constant damage function we observe sustainability problems in the GS1 scenario (Fig. 7). The underlying trend follows the original estimates but from 1990 to 95 total environmental damages are depressed by 3 percentage points in the GS1 scenario (consequently GS1 is 3% higher). Negative savings remain in 1992 and savings are below 1% during the early 1990s. The effect is much less pronounced for GS2 and GS3 with environmental damages lowered by 1 percentage point. As time passes the marginal damages rise closing the disparity between the two sets of estimates and from 1999 the disparity is less than 1 percentage point across all scenarios. Including changes in agricultural land value would lead to negative savings from 1990 to 1995.

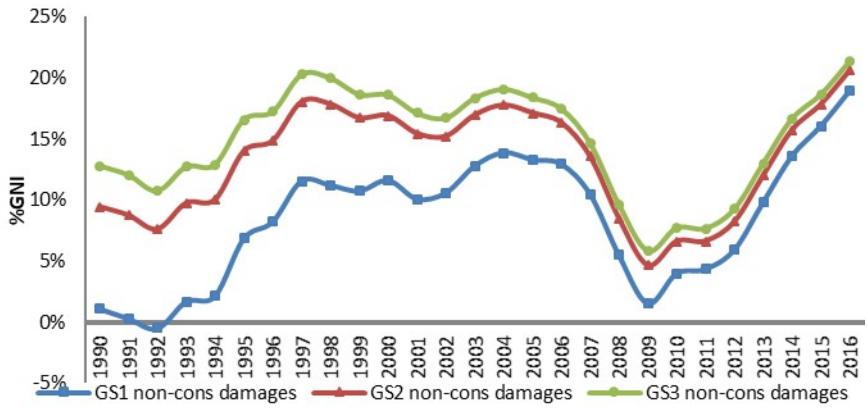


Figure 7: Range of Genuine Savings estimates employing non-constant marginal damage costs 1990-2016

4.2 Comparisons with existing estimates

The World Bank provides estimates of GS for most countries in the world, including Ireland. F&M compile country specific Irish GS from 1995 to 2005. The results presented here represent an important refinement of the rough World Bank estimates used in that previous work and is the only other country specific Irish GS study. F&M's main findings were that Irish savings are smaller than the World Bank's figures and even negative for several years. Edens (2013) questions the valuation of the extended environmental damages driving F&M's results. Ferreira and Moro (2013) offer a response to Edens, acknowledge the issues raised and amend their results. In the discussion below we compare our results with the corrected estimates from Ferreira and Moro (2013). The World Bank provides a dataset for most countries in the world from 1970.[51]

Following updated methods, Irish GS as reported by the World Bank now only covers 2005–2016. Estimates are unavailable pre 2005 as Irish GNS data is missing. All other components are included thus to obtain a consistent series for a longer comparison we use the GNS from the Irish national accounts. In comparison with the existing estimates, our results differ most considerably in terms of the range of environmental damages employed. We utilise more recent damage cost estimates and an expanded set of pollutants[52] (as discussed in Section 3.1). Differences will also emerge through revisions to the accounts by the Irish CSO and the method used by the World Bank to convert from dollars to euro (as discussed in section 3.3). Differences will also emerge through revisions to the accounts by the Irish CSO and the method used by the World Bank to convert from dollars to euro.[53] Further differences emerge in relation to natural capital but have a negligible impact on the overall results (see Section 3.2).

Table 3 compares our mid-range GS estimates (GS2) with the existing estimates from the literature over the period observed by F&M (1995–2005).[54] Column (4) presents the World Bank's savings rates using the older methods and column (5) presents the estimates from the updated methodology.[55] Our estimates are substantially lower than both sets of the World Bank's estimates at the beginning of the period. Comparing columns (2) and (3) where human capital accumulation equates the returns to education we see our GS2 estimates are on average 2 percentage points below Ferreira and Moro (2013). Environmental damages drive this disparity, GS1 estimates are on average 7 percentage points lower and GS3 1 percentage point lower. A trend of rising savings is observed across all studies, except for the older World Bank estimates which record a decline in the middle of the period, this decline emanates from unrealistically large natural capital depreciation demonstrating a key weakness of the older methods.[56] Comparing columns (4) and (5) illustrates the notable change caused by the updated methods employed by the World Bank.

Table 3: Comparisons with exiting estimates from the literature 1995-2005

[51] https://datacatalog.worldbank.org/dataset/adjusted-net-savings

[52] In relation to F&M we add NH_3, CO, CH_4, NMVOC. These additions represent, on average, an additional €270m- €1.4bn per year (in 2000 prices) representing 20% of our average total annual damages.

[53]See: https://datahelpdesk.worldbank.org/knowledgebase/articles/378832-the-world-bank-atlas-method-detailed-methodology)

[54] Column (3) is estimated from Ferreira and Moro (2013) Figure 3.

[55] As reported in F&M table 1

[56] F&M figure 5 illustrates that the Bank estimated depreciation of natural capital at around €5bn per year from 1998.

Year	(1) GS2 Human Capital = Education Expenditure	(2) GS2Human Capital = Returns to education	(3) Ferreira and Moro (2013) including corrections Human Capital = Returns to education	(4) World Bank older methods as reported in Ferreira and Moro (2011)	(5) World Bank (2018) * indicates GNS figure from Irish Accounts is used to obtain an estimate
1995	13%	8%	8%	19%	16%*
1996	14%	9%	12%	22%	16%*
1997	17%	12%	15%	24%	20%*
1998	17%	13%	17%	18%	20%*
1999	16%	12%	16%	16%	19%*
2000	16%	13%	16%	11%	19%*
2001	15%	12%	13%	14%	17%*
2002	14%	12%	12%	14%	17%*
2003	16%	14%	15%	18%	18%*
2004	17%	15%	15%	18%	19%*
2005	17%	14%	15%	19%	21%

Table 4 compares our range of GS estimates with the World Bank for those years outside of the period covered by F&M. The trends are common across the range of estimates and follow the four periods described in Section 4. From 1990 to 1994, GS1 savings are 14 percentage points below the World Bank's, on average. GS2 is 4 percentage points lower and GS3 is 1 percentage point below. The large disparity is primarily the result of our extended environmental damages. Fig. A2 in Appendix A illustrates our GS1 estimate with the World Bank's over the entire period. From 2006 to 2013 the disparity shrinks, our GS1 is lower on average by 4 percentage points, GS2 is 2 percentage points lower and GS3 is 1 percentage point below. The shrinkage largely reflects the extended environmental damages fading away as total pollutant damages are considerably lower than the early 1990's. From 2013 GS3 savings are higher than the World Bank's caused by our NNS estimate, taken from the official national accounts, being higher than the World Bank's figures. Earlier we noted the improvements in the World Bank's methods, while the modern estimates appear to better reflect underlying GS the need for country level refinement still appears necessary. Outside of the limited coverage of air pollutants, another issue for Ireland in the updated World Bank dataset is the missing data for GNS as well as for mineral depletion, for which there is no data in eleven out of the fourteen years from 1990 to 2003.

Table 4: Comparisons with the World Bank (2018) for selected years

Year	(1) GS1 Human Capital = Education Expenditure	(2) GS2 Human Capital = Education Expenditure	(3) GS3: this paper Human Capital = Education Expenditure	(2) World Bank (2018) * indicates GNS figure from Irish Accounts is used to obtain an estimate
1990	-2%	8%	12%	13%*

1991	-3%	7%	11%	12%*
1992	-4%	6%	10%	10%*
1993	-1%	9%	12%	13%*
1994	0%	9%	12%	13%*
2006	13%	16%	17%	18%
2007	11%	13%	14%	15%
2008	6%	8%	9%	11%
2009	2%	4%	6%	8%
2010	4%	6%	8%	8%
2011	4%	6%	8%	8%
2012	6%	8%	9%	10%
2013	10%	12%	13%	12%
2014	14%	16%	17%	15%
2015	16%	18%	19%	16%
2016	19%	20%	21%	21%

5. Conclusions

We constructed a time-series of genuine savings estimates predominantly from official Irish sources and enhanced exiting estimates in several other ways. The methods employed are applicable to many other countries. Our extended pollutant damages offer the most comprehensive coverage across the literature surveyed. We applied a novel method to aid the assessment of the relevant property rights designation required when accounting for the transboundary impacts of CH4 and CO2 and find the 'polluter pays' principle may be more appropriate for Ireland. Augmented natural capital depletion estimates include country-specific factors, namely peat harvest, changes in agricultural land value and forestry growth. Finally, we refined the method developed by Ferreira and Moro (2011) to estimate human capital accumulation as the returns to education in addition to the commonly used and much criticised expenditure method. While the focus of the analysis in this paper was on Ireland the adjustments to the method and the impacts observed from the inclusion of the additional pollutants have important implications for the assessment of GS estimates more broadly. We show that in sharp contrast to the estimates of the World Bank a developed economy with a low endowment of mineral and energy resources can exhibit signs of unsustainability (although highly sensitive to the marginal damage costs employed). Comprehensive accounting for pollution damages yields this surprising result. Our results demonstrate the potential benefits of pollution reductions and provide a reminder that a system of regulations prioritising one particular problem such as carbon dioxide emissions at the expense of other damaging air pollutants may result in misguided public policy. Another key policy implication is that governments should be cognisant of the theoretical literature which suggests wealth should be the focus of sustainability assessments rather than national income. Governments constructing sustainable development indicator sets and/or implementing natural capital accounting systems should also be aware of the limitations the World Bank ANS indictor. Our results suggest construction of country-specific GS estimates that focus on individual national characteristics and data can lead to a considerable divergence from the ANS estimates despite considerable methodological improvements. We echo the repeated calls for the extension of additional pollutants within empirical GS applications (Ferreira and Vincent, 2005; Pillarisetti, 2005; Dietz and Neumayer, 2006; Atkinson and Hamilton, 2007; Neumayer, 2013; Boos, 2015; Hanley et al., 2015). Ireland's expanded pollution damage adjustments were as large as 18% of GNI compared with a maximum of less than 1% of GNI in the World Bank dataset. This is further compounded by noting Ireland's marginal damage costs are below the European average for all pollutants and considerably below the PM and NH3 range contained in EEA (2014). Considering that from 1990 to 2016 the average GS rate for the EU aggregate contained in the World Bank dataset was 9% of GNI, a country-specific extension of pollutant damages may have a sizeable impact. Given the rough and ready assumptions required to compile GS estimates, another promising area for future work would be adding to the limited literature econometrically testing the hypothesised relationships between GS and long-term welfare. Long-run tests have been applied in the cases of Britain, Germany and the US from 1765 to 2016 (Greasley et al., 2014), Sweden from 1850 to 2000 (Lindmark et al., 2018), New Zealand from 1950 to 2015 (Qasim et al., 2018), Australia from 1861 to 2011 (Greasley et al., 2017) and several developing and developed economies from 1900 to 2000 (Blum et al., 2017).

Our findings are limited by the fact we do not include some other important forms of natural capital (e.g. biodiversity loss, fisheries, and soil degradation). The valuation techniques employed also fail to capture lost ecosystem services other non-market benefits provided by peatlands. This is particularly salient given the rapid depletion of Irish peatlands and repeated criticism of government policy regarding peat extraction. This has obvious implications for the broader development of environmental policy and cost-benefit analysis of natural resources in Ireland. Finally, we note that future work enhancing the coverage of historical data to Irish natural capital stocks would be desirable given the history of some renewable stocks being treated as extractive resources such as fisheries, in particular, native oyster beds (Wilkens, 2004) and forestry (O'Carroll, 2004).

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Appendix A:

Table A1: Data sources

Natural Capital	Production/Extraction	Prices	Costs	Lifetime
Zinc Lead Silver	DCCAE	World Bank Commodity Database	Ferreria and Moro (2011). CSO Historical Earnings	2026 - Boliden (2018)
Natural Gas	BGE Accounts, Eurostat, DCCAE	World Bank (2018) Unit Rents		2030 – Reserves to Production
Coal	DCCAE	World Bank (2018) Unit Rents		1993- Cessation of production
Peat	Bord na Mona Accounts	Bord na Mona Accounts		Bord na Mona (2015)
Forestry	Teagasc Annual Forestry Statistics, DAFM (2012;2018)	FAO Timber Database	17% Rental Adjustment from World Bank (2018)	Renewable
Pollutants	**Damage Costs**			**Emissions**
CO_2	Method A: The polluter pays principle: damages reflect the global social cost of emissions. The costs employed reflect the range of estimates across the literature: Method B: Ireland is attributed the fraction of Earth's atmosphere reflecting its relative size (GDP). Methods from Arrow et al. (2012). Global GDP, Irish GDP and Global Emissions from World Bank (2018). Damage Costs are as in Method A			
CH4	Method A: Marten et al 2015 and Waldhoff et al (2014) Method B: Same procedure as described for CO_2			Environmental Protection Agency (2018), Irish Central Statistics Office (2018), UNFCCC Database
CO	Shindell (2015) and Repetto et al. (1989)			
SO2 NOX PM2.5 NH3 NMVOC	EEA (2014) and EnvEcon (2015)			
Human Capital	**Estimates**			
Education Spending	World Bank (2018)			
Returns to Eduction	Methods from Ferreria and Moro (2011) Labour Force and Educational Attainment from CSO Census Data Earnings Data from CSO Statistical Yearbooks Returns to Education from Barret et al. (2002)			

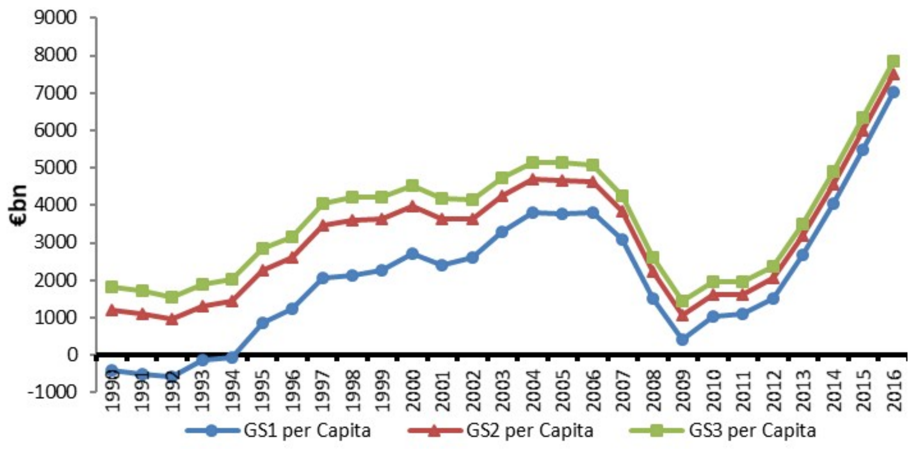

Figure A1: GS Per Capita

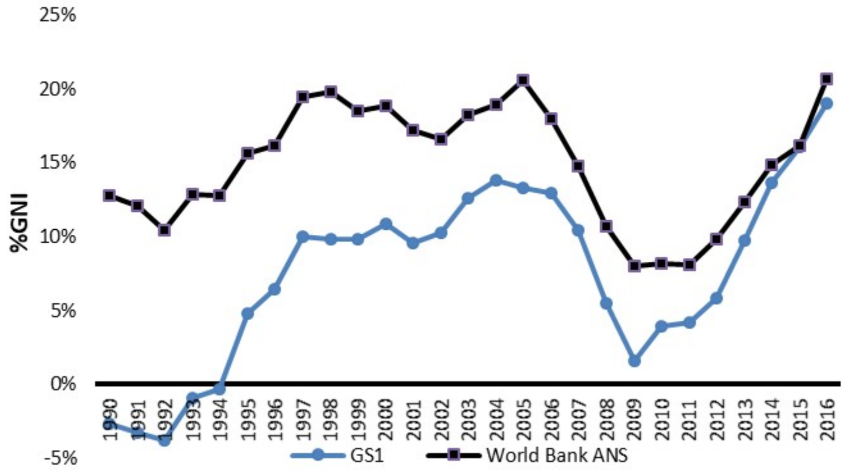

Figure A2: GS1 and World Bank ANS 1990-2016

Appendix B: Data Appendix

Depletion Methods

To compute depletion estimates we apply the simple net present value method (SNPVM) (El Serafy, 1989). Following standard economic theory, by conceptualising the value of an asset as the discounted sum of rents over the asset's lifetime the value for a non-renewable (S) at time t is:

$$S_t = \sum_{n=0}^{T} ((p_{t+n} - c_{t+n})R_{t+n})/(1+r)^n \qquad \text{(B.1)}$$

Where p and c represent the price and cost of a unit extracted. R is the quantity extracted, r is the discount rate and T is the final year of extraction. For GS calculations we are interested in the change in the asset's value during the accounting period. This change in value is the forgone value of keeping the resource intact at time t minus the current economic rent:

$$S_{t+1} - S_t = \frac{rS_{t+1}}{1+r} - (p_t - c_t)R_t \qquad \text{(B.2)}$$

The SNPVM assumes constant unit rents and extraction rate (see Perman et al., 2003). Under these assumptions (B.1) can be rewritten as

$$S_t = \sum_{n=0}^{T} (p - c)R/(1 + r)^n \qquad \text{(B.3)}$$

and (B.2) can be rewritten:

$$S_{t+1} - S_t = Ds_t = -(p - c)R/(1 + r)^T \qquad \text{(B.4)}$$

Metals and minerals

We include depreciation for all major reserves extracted in Ireland from 1990.[57] To account for the depletion of metal and mineral resources F&M obtained a joint extraction cost estimate of $475-$525 per tonne in 2008 from the Department of Communications, Climate Action and Environment (DCCAE).[58] We take the mid-point and convert to euro using OECD (2018), then distribute the joint-cost in proportion to extraction in 2008 (lead 88%, zinc 11% & silver 1%).[59] We construct a historical earnings index using Irish Central Statistics Office (CSO) data to deflate production costs and obtain a nominal series.[60] Prices are from the World Bank's commodity database[61] and the lifetime of mineral resources is set at 2026 coinciding with the expected closure of the Tara mine (Boliden, 2018).[62]

Energy resources

To compute our natural gas depletion estimates we utilise unit rents contained in the WDI dataset[63] and discount using the SNPVM. We estimate the lifetime by taking expected reserves from the Corrib gas field (954,616 TJ) to production utilising supply projections from Gas Networks Ireland's Network Development Plan (GNI,

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[57] Lead, zinc, and silver we exclude barytes (1990-1993) and gypsum (1990-2005) due to data limitations.
[58] The now retired Ben Dhonau provided the estimate, we were unable to obtain a new estimate from DCCAE.
[59] https://data.oecd.org/conversion/exchange-rates.htm.
[60] Constructed from data on average earnings in the mining and quarrying industry from 1995-2015 and industrial workers in the mining, quarrying and turf sector from 1990-1994 http://www.cso.ie/en/statistics/earnings/historicalearnings1938-2015/
[61] http://www.worldbank.org/en/research/commodity-markets.
[62] https://www.boliden.com/operations/exploration/mineral-reserves-and-mineral-resources# F&M set the lifetime to 2017 the expected closure at the time of publication.
[63] See https://databank.worldbank.org/data/home.aspx

2016).[64] Ireland extracted limited coal reserves during the observed period. Production of 25kt in 1990 fell to 1kt per year until production ceased in 1993. We use the World Bank's unit rents and discount using SNPVM with the lifetime set to 1993. We obtain the peat unit rent by multiplying the annual operating profit (per tonne of peat produced) by the percentage of revenues arising from milled peat activities in each year from BnM accounts.[65] The resource lifetime is set to 2030 (Bord na Mona, 2015) and discounted using the SNPVM. The World Bank excludes peat depletion, we include estimates by utilising data contained in Bord na Mona (BnM) annual reports.[66] BnM, a state-owned enterprise was set up in 1946 to develop peat resources during WWII and is Ireland's main producer of peat (Gaffney et al, 2017).

Forestry

Historically, human activity and climate deterioration caused the near complete deforestation of Ireland (O'Carroll, 2004). Forestry represented less than 2% of land cover from the mid-1800's to the mid-1900's (DAFM, 2016). Modern Irish forestry policy has resulted in land cover growing to 10.5% by 2015 (CSO, 2017) and government policy is to reach 18% by 2020 (DAFM, 2016). Estimates of the standing stock were made utilising land cover data from Teagasc Annual Forestry Statistics reports[67] as well as afforestation rates and estimates of the total standing growing stock contained in the National Forest Inventory (DAFM, 2018; DAFM, 2012). Costs are estimated as the European average rental adjustment of 17% from World Bank (2018).[68] It is further assumed 30% of the increased stock will be economic this is toward the upper limit in Bolt et al. (2002).

Changes in Agricultural Value

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[64] The projections yield an 11 year life set to 2026 comparable to the rough lifetime of 15 years on the DCCAE website: https://www.dccae.gov.ie/en-ie/natural-resources/topics/Oil-Gas-Exploration-Production/corrib-gas-field/Pages/Corrib-Gas-Field.aspx

[65] For 2012 we take the average unit rent of the previous five years as BnM recorded an operating loss causing a negative unit rent for 2012.

[66] This method was developed in F&M utilising BnM reports from 2002/03 – 2004/05 and imputing earlier estimates. Our data is taken directly from the BnM accounts available online from 1946 here: http://opac.oireachtas.ie/liberty/libraryHome.do

[67] From various years available https://www.teagasc.ie/crops/forestry/advice/general-topics/statistics-on-forestry-in-ireland/

[68] Prices are regionally weighted from the FAO timber database following the World Bank (2018) to smooth out the variability in the Irish Price. The average in nominal terms from 1990-2016 is €32/m3 for the regional price compared to €28/m3 for the Irish price.

The stock value of cropland and pastureland, V_t, is calculated as the present value of returns to land using the following equation:

$$V_t = \overline{R_t} + \frac{\overline{R_t}}{r-g} \qquad \text{(B.5)}$$

where $\overline{R_t}$ represents the lagged, five-year moving average of the total value of rents from crop and livestock products in the present year t to year t – 4; r is the annual discount rate of 4 percent (we also test 2% and 6) and g is the annual rate of growth in agricultural productivity assumed to be 0.97% for crops and 0.89% for livestock (the growth rates for high income countries used in World Bank, 2018). Land area is assumed constant. Our cropland estimates include oats, barley, potatoes, wheat, sugar beet and mushrooms. Our pastureland estimates include milk, bovine meat, pig meat and sheep meat. Data on production and producer prices are from Eurostat, Bord Bia and the Irish CSO and we follow the methods outlined in World Bank (2018). The annual rents for cropland products are calculated as follows:

$$R_{k,t} = q_{k,t} * p_{k,t} * a_g \qquad \text{(B.6)}$$

where $R_{k,t}$ represents rents from crop k harvested in year t; $q_{k,t}$ denotes production for that individual crop; $p_{k,t}$ denotes the unit price; and a_g is the average rental rate assumed constant at 0.17 (the western Europe rate from World Bank, 2018). Livestock rents are calculated as:

$$R_{k,t} = (q_{k,t} * p_{k,t} * 2a_g)e_c + (q_{k,t} * p_{k,t} * a_g)(1 - e_c) \qquad \text{(B.7)}$$

Where R, p, q and a are as already defined, e_c is the share of livestock production in extensive systems. The rental rate is assumed to be twice that for intensive systems. The same rental rates assumed for crop products are assumed for livestock products in intensive systems. The share of livestock in extensive systems is determined from percent of ruminant meat produced in grazing systems, as estimated by the FAO for its Global Livestock Environmental Assessment Model. Total rents are estimated by summing up each individual crop.

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