AUGMENTED SUSTAINABILITY MEASURES FOR SCOTLAND

John C. V. Pezzey

Centre for Resource and Environmental Studies
Australian National University, Canberra, ACT 0200, Australia, and
Visiting Fellow, Department of Economics, University of Bath, U.K.
Tel/fax: +61 2 6125 4143/0757 E-mail: pezzey@cres.anu.edu.au

Nick Hanley

Department of Economics, University of Glasgow, Glasgow, G12 8RT, Scotland

Karen Turner

Fraser of Allander Institute, University of Strathclyde, Glasgow, G4 0LN, Scotland

and

Dugald Tinch

Department of Economics, University of Glasgow, Glasgow, G12 8RT, Scotland

15 May 2003

Abstract: We estimate and compare two empirical measures of the weak sustainability of an economy for the first time: the change in augmented green net national product (GNNP), and the interest on augmented genuine savings (GS). Yearly calculations are given for each measure for Scotland during 1992-99. Augmentation means including, using projections to 2020, production possibilities enabled by exogenous technical progress or changing terms of trade. In passing, we clarify the treatment of environmental expenditures in green accounting. The change in augmented GNNP and interest on augmented GS are both always positive, showing no sustainability problem for Scotland; but the former greatly exceeds the latter, showing an unresolved problem with the theory.

Keywords: sustainability, Scotland, genuine savings, green NNP, augmentation
JEL codes: D90, O47, Q01

TABLE OF CONTENTS

1. INTRODUCTION

Sustainable development is now an important policy priority for many EU countries, and recent years have seen much interest in improving country-level ("macro") indicators of "sustainability". Many developments have recently been made in the economics of sustainability, particularly the theory and practice of measuring it for a whole country (see for example Asheim 1997, Pezzey 1997, Vincent et al 1997, Weitzman 1997, Dasgupta 2001, Pemberton and Ulph 2001, Asheim and Weitzman 2001, hereafter AW, and Pezzey and Toman 2002, hereafter PT). Some of these developments are applied here to the case of Scotland. AW showed that in a theoretical, present-value-maximising economy, two measures are always equal: the change in (time derivative of) real, green net national product (GNNP), and the real interest rate multiplied by genuine savings (GS), a measure of aggregate net investment across the whole economy. PT used this result to show theoretically that if either measure is zero or negative at some time, the economy is *un*sustainable then; they also "augmented" the tests to include exogenous changes in production possibilities over time.[1] The most obvious sources of such changes are exogenous technical progress, as analysed and estimated by Weitzman for the USA, or changing terms of trade, as analysed and estimated by Vincent et al for Indonesia as a pure oil-exporting economy. All these papers assume smooth production sets and utility functions, and so fall within the neoclassical or "weak" paradigm of sustainability measurement. This means that everything can in principle be priced, that there is no limit to substituting human-made capital for environmental resources, and that any computation problems caused by the uncertainty, irreversibility or threshold effects of overstressed ecosystems are assumed away.

1. PT's tests used the phrase "net investment" instead of "genuine savings".

Hanley et al. (1999) estimated GNNP and GS for Scotland for 1980-1993, along with five other economic and non-economic measures of Scottish "sustainability", but they neither included any augmentation terms, nor compared GNNP change with the interest on GS. They also made some approximations to cope with Scotland not having complete national accounts of a conventional kind, because it is in many ways a region of the UK economy rather that a national economy in its own right. Using the same approximations, we extend their approach here, by estimating the change in augmented GNNP and the interest on GS for Scotland for the period 1992-1999, using projections or scenarios up to 2020 for future technical progress and changes in terms of trade in order to calculate the augmentation terms. We are interested in both the practical difficulties and wider implications of using empirical data to test the theoretical relationship between our two chosen measures. In so doing, we will also clarify some points of principle about accounting for expenditures on environmental improvement, and about choosing between the marginal cost and marginal benefit of any such expenditure when they are not equal.

The paper is organised as follows. Section 2 summarises existing theory in AW and PT on national income accounting and sustainability for a fairly general theoretical economy. Section 3 describes a more specific economy with realistic features, to be estimated for Scotland, and makes the points of principle just mentioned. Section 4 lists the data sources used for Scotland. Section 5 gives the empirical results, including three sensitivity tests. All results show the change in augmented GNNP to be much greater than the interest on GS, showing a lack of agreement with AW's theoretical result. Section 6 concludes.

2. A SUMMARY OF THE BASIC THEORY TO BE USED

We summarise here the general economy considered by AW and PT, which should be consulted for further details. An extended consumption vector $\mathbf{C}(t)$, including amenities, determines the instantaneous utility $U(\mathbf{C}(t))$ of a representative consumer at time t. Vector $\mathbf{K}^{\dagger}(t)$, where $\mathbf{K}^{\dagger} := (\mathbf{K},t)$, comprises $\mathbf{K}(t)$ (of maybe different dimension to $\mathbf{C}(t)$), the economy's controlled, productive stocks of capital (physical, financial, natural, human, knowledge, etc), and time t itself, treated as an uncontrolled, productive stock as in Pemberton and Ulph (2001) (uncontrolled because $\dot{t} = 1$ always, independent of any economic choices). Time is treated like this so that the analytical framework includes changes in production possibilities − for example from technical progress or shifts in terms of trade − which happen exogenously, just because time passes. Any variable containing either time as a stock, or some variable corresponding to time as a stock, will be called *augmented* and denoted with a dagger superscript (†).

We define sustainability thus:

an economy is *sustainable* at time $t \iff U(\mathbf{C}(t)) \leq U^m(t)$; [1]

where $U^m(t)$ is maximum sustainable utility at t, defined by

$$U^m(t) := \max U \text{ s.t. } U(\mathbf{C}(s)) \geq U \text{ for all } s \geq t. \quad [2]$$

We assume the economy always follows a *PV-optimal* (or just *optimal*) path of development, that maximises the present value (PV) of utility using a constant discount rate $\rho > 0$, where $\Pi\{\mathbf{K}^{\dagger}(t)\}$ is the economy's production possibilities set:

$$\underset{\mathbf{C},\dot{\mathbf{K}}}{Max} \quad W\{(\mathbf{C}(t)\} := \int_0^{\infty} U[\mathbf{C}(t)]e^{-\rho t}dt \text{ s.t. } [\mathbf{C}(t),\dot{\mathbf{K}}^{\dagger}(t)] \in \Pi\{\mathbf{K}^{\dagger}(t)\}. \quad [3]$$

Denote variables on the solution path to this problem by *, and the shadow investment prices on it by $\Psi(t)$. Define **P** and $\mathbf{Q}^{\dagger} := (\mathbf{Q}, Q^t)$, the vectors of real Divisia accounting prices for extended consumption, and for capital stocks (where Q^t is the accounting price for t, the stock of time) by

$$\mathbf{P}(t) := [(\partial U/\partial \mathbf{C}^*)(t)]/\Pi(t) \quad \text{and} \quad \mathbf{Q}^{\dagger}(t) := \Psi^{\dagger}(t)/\Pi(t), \qquad [4]$$

while the real interest rate is

$$r(t) := \rho - \dot{\Pi}(t)/\Pi(t), \qquad [5]^2$$

where Π (denoted $\lambda\pi$ in AW) is defined by the Divisia condition for the price vector **P** to represent real prices in some sense:

$$\Pi(t) \text{ is s.t. } \dot{\mathbf{P}}(t).\mathbf{C}^*(t) = 0 \text{ for all times } t. \qquad [6]$$

Defining real, augmented green net national product in real Divisia prices and augmented genuine savings as

$Y^{\dagger}(t)$	:=	$\mathbf{P}(t).\mathbf{C}^*(t)$	+	$\mathbf{Q}^{\dagger}(t).\dot{\mathbf{K}}^{*\dagger}(t)$	[7]
augmented GNNP	:=	consumption expenditures	+	augmented GS,	

the key results in AW and PT are respectively

$$\dot{Y}^{\dagger}(t) = r\mathbf{Q}^{\dagger}(t).\dot{\mathbf{K}}^{*\dagger}(t), \quad \text{and} \qquad [8]$$

$$\{\dot{Y}^{\dagger}(t) \le 0 \ \text{ or } \ r\mathbf{Q}^{\dagger}(t).\dot{\mathbf{K}}^{*\dagger}(t) \le 0\} \ \Rightarrow \ \{U(t) > U^m(t)\}; \qquad [9]$$

and from PT's equation (4.21), $Q^t(t)$, henceforth called the *value of time*, is

$$Q^t(t) = \int_t^{\infty}[\partial Y(s)/\partial s]\exp[-\int_t^s r(z)dz]ds. \qquad [10]$$

So in theory, if at any given time either $\dot{Y}^{\dagger}(t)$, the time change in augmented GNNP, or $r(t)\mathbf{Q}^{\dagger}(t).\dot{\mathbf{K}}^{*\dagger}(t)$, the interest on augmented GS, is not

2. AW used R for the real interest rate, but we use R for resource depletion rates.

positive, then the economy is *un*sustainable at that time ($U(\mathbf{C}^*(t) > U^m(t))$. This motivates our measurement here of $\dot{Y}^\dagger$ and $r\mathbf{Q}^\dagger.\dot{\mathbf{K}}^{*\dagger}$ for Scotland, to explore of how valid and therefore useful this theory might be in practice.

But a real economy like Scotland will fail to satisfy many of the assumptions made above. We do not even know if economies do seek optimality as defined by problem [3]. Many environmental and other elements of the consumption or capital vectors will remain as uninternalised externalities, and so make the economy sub-optimal. Data for many variables will be unavailable because they are either inherently hard to obtain, or not collected for Scotland as opposed to the UK. It is somewhat paradoxical to use AW's optimal growth results as the basis for sustainability measurement in imperfect economies, but there is currently little alternative, if governments wish to use macro indicators of sustainability which have at least some grounding in economic theory (Hanley and Atkinson 2003).

3 A THEORETICAL FRAMEWORK FOR THE SCOTTISH ECONOMY

We describe here a more specific theoretical model of the Scottish economy that we use for our empirical work in Sections 4 and 5. Like the "more specific economy" in PT (pp186-8), it is a particular form of the above general model. It uses various features found in 'green accounting' models such as Hartwick (1990), Hamilton (1994, 1996) and Vellinga and Withagen (1996), selected partly with the existence of data series of acceptable quality in mind. For this model we derive expressions for $r\mathbf{Q}^\dagger.\dot{\mathbf{K}}^\dagger$ (the interest on augmented GS), hence $Y^\dagger$ (augmented GNNP) and $\dot{Y}^\dagger$ (change in augmented GNNP), which allow us to use the one-sided sustainability tests in equation [9]. The model has extraction, with perhaps discovery and/or renewal, of five natural resource stocks; investment in and depreciation of human-made capital; foreign trade in natural resources and a consumption/investment good, resulting in a stock of foreign capital; production using capital and resource inputs, and with exogenous changes in production from both technical progress and changes in the terms of resource trade; six flows of pollutants; and one amenity improvement. Details are as follows, with all variables assumed to be *endogenous* functions of time, unless they are specifically noted as parameters, or are exogenous functions of time denoted by an explicit dependence on t.

3.1 Natural resources

We designate Scotland's stocks of five renewable and non-renewable resource stocks by the vector $\boldsymbol{S}(t) := (S^1(t),...,S^5(t))$, being respectively the stocks of coal, aggregates (sand and gravel), North sea oil, wild (not farmed) fish, and commercial forestry. (Although the North Sea has both oil and gas, only oil was considered for Scotland, since about 80-90% of the UK's gas stocks can be estimated to lie on the English side of a notional marine border between the two countries.) These resources are depleted at rate $\boldsymbol{R}$, equal to domestic resource use $\boldsymbol{R}^d$ plus resource exports $\boldsymbol{R}^X$ minus resource imports $\boldsymbol{R}^M$ (all vectors of the same dimension as $\boldsymbol{S}$):

$$\boldsymbol{R} = \boldsymbol{R}^d + \boldsymbol{R}^X - \boldsymbol{R}^M. \qquad [11]$$

They are also discovered at rate $\boldsymbol{D}$, and grow at a stock-dependent rate $\boldsymbol{G}(\boldsymbol{S})$ (non-zero only for fish and forests), so the net rate of stock changes is:

$$\dot{\boldsymbol{S}} = \boldsymbol{D} + \boldsymbol{G}(\boldsymbol{S}) - \boldsymbol{R} = \boldsymbol{D} + \boldsymbol{G}(\boldsymbol{S}) - \boldsymbol{R}^d - \boldsymbol{R}^X + \boldsymbol{R}^M, \qquad [12]$$

or for each individual resource

$$\dot{S}^i = D^i + G^i(S^i) - R^{di} - R^{Xi} + R^{Mi}, \quad i = 1,..,5. \qquad [13]$$

For practical estimations, wherever data on the change $\dot{S}^i$ of a resource stock are available directly, they are used instead of computing $\dot{S}^i = D^i + G^i - R^i$.

3.2 Trade, interest, production, and manmade capital

We use the conventional notation X for the total value of exports and M for the total value of imports, so that Scotland's trade balance flow is $X-M$. Scotland owns a stock K^f of net foreign capital (or debt if $K^f < 0$), held privately or by the government, which earns a return at the exogenous, constant world interest rate r.[3] The foreign capital stock then grows as a result of interest on the capital plus the trade balance:

$$\dot{K}^f = rK^f + X - M. \qquad [14]$$

Turning to domestic variables, there is a stock K of manmade physical capital in Scotland, which increases at the rate of gross investment (Domestic Fixed Capital Formation) I minus depreciation δK:

$$\dot{K} = I - \delta K. \qquad [15]$$ [4]

Production $F(K,\boldsymbol{R}^d,t)$ is assumed to depend positively on inputs of capital K, the physical vector of domestic resource use $\boldsymbol{R}^d$, and time t (the effect of exogenous technical progress). The combined value of production F, and of net imports $M-X-\boldsymbol{Q}^R.(\boldsymbol{R}^M-\boldsymbol{R}^X)$ of the consumption/investment good (but not resources), is distributed among consumption C; gross investment I; firms' abatement current expenditure a; government spending J on agri-

---

3. The world interest rate could of course vary over time. This would result in an extra term $\dot{r}K^f$ in the integrand of Q^t in equation [23] below (see PT, equation (4.40)).

4. Unlike PT, we have no separate measure of abatement capital, there denoted as $K_a(t)$, or its role in abating pollution rather than producing output.

environmental (rural landscape) improvement schemes; firms' resource discovery costs $V(\boldsymbol{D},\boldsymbol{S})$ with $V_{\boldsymbol{D}} > \mathbf{0}$; and firms' extraction costs $f(\boldsymbol{R},\boldsymbol{S})$ with $f_{\boldsymbol{R}} > \mathbf{0}$, $f_{\boldsymbol{S}} < \mathbf{0}$:

$$F(K,\boldsymbol{R}^d,t) + M - X - \boldsymbol{Q}^R.(\boldsymbol{R}^M - \boldsymbol{R}^X) = C + I + a + J + V(\boldsymbol{D},\boldsymbol{S}) + f(\boldsymbol{R}^d + \boldsymbol{R}^X - \boldsymbol{R}^M,\boldsymbol{S}) \quad [16]$$

Hence $$\dot{K} = F(K,\boldsymbol{R}^d,t) + M - X - \boldsymbol{Q}^R.(\boldsymbol{R}^M - \boldsymbol{R}^X) - C - a - J - V(\boldsymbol{D},\boldsymbol{S}) - f(\boldsymbol{R}^d + \boldsymbol{R}^X - \boldsymbol{R}^M,\boldsymbol{S}) - \delta K \quad [17]$$

3.3 Determinants of utility

Instantaneous utility U depends on consumption $C(t)$; an emissions vector $\boldsymbol{E}(t)$; and the flow of "added environmental quality" $B(J(t))$, measured in some physical index of improved amenity and biodiversity on agricultural land, which results from a total rate of government spending $J(t)$ on "agri-environmental" schemes:

$$U(t) = U[C(t),\boldsymbol{E}(t),B(J(t))], \quad U_C,\ U_B > 0, \quad U_{\boldsymbol{E}} < \mathbf{0} \quad [18]^5$$

The extended consumption vector then is $\mathbf{C} := (C,\boldsymbol{E},B)$. This creates real prices P^C for consumption, $\boldsymbol{P}^{\boldsymbol{E}}$ (also a vector) for emissions, and P^B for agri-environmental quality, which together satisfy the Divisia property in equation [6] and thus make $P^C C + \boldsymbol{P}^{\boldsymbol{E}}.\boldsymbol{E} + P^B B$ an index of utility measured in consumption units. Emission flows $\boldsymbol{E} := (E^1,...,E^6)$ are measured for six pollutants: sulphur dioxide (SO_2), particulate matter less than 10 micrometres

---

5. Our theoretical measures therefore ignore any effects of emissions on productivity (via the production function $F(.)$), as opposed to direct amenity effects on utility. This assumption accords well with the dominant focus on health effects that underlies our empirical estimates of emissions damages reported in Section 4.2. See also the end of Section 3.5 on the choice of how agri-environmental spending J appears in this utility function.

in diameter (PM10), carbon monoxide (CO) and three greenhouse pollutants: carbon dioxide (CO_2), nitrous oxide (N_20) and methane (CH_4).[6] Total abatement spending a is notionally divided into separate spending levels $\{a^i\}$ with $a = \Sigma_{i=1}^{6} a^i$, and each emission level $E^i(\boldsymbol{R}^d, a^i)$ depends on domestic resource use and abatement expenditure.

It will be convenient to denote:

$e^i(t) := 1/(-\partial E^i/\partial a^i)$, the marginal abatement cost for pollutant i, [19]

which in an optimal economy will equal the marginal abatement benefit for the pollutant; and for neatness we use vector notation $\boldsymbol{e} = (e^1,...,e^6)$. We likewise denote:

$b(t) := 1/B'(J)$, the marginal cost of improving agri-environmental quality. [20]

In the absence of sufficient data, we assume that all marginal abatement and improvement costs are *constant* for all pollutants during the period under consideration. We show later in Appendix 1 that the "price of consumption" P^C (i.e. price relative to the consumption-plus-environmental-values-aggregate which is dollarised utility) is then constant, and can be set to unity. The empirical validity of this assumption is very difficult to test, but it may deserve further investigation in the light of evidence on income elasticities of demand for environmental quality.

---

6. Though it is the flows and not the concentrations of greenhouse pollutants that will be measured, the marginal damage cost of each of these takes into account its atmospheric lifetime effect or 'global warming potential'.

3.4 Accounting for environmental expenditures by firms, government and households

In Section 3.5 we will give a formula for calculating augmented GNNP indirectly, starting from data on NNP (itself derived from GDP using NNP = GDP − $\delta K + rK^f$), rather than directly from data on consumption and net investments. In reaching the indirect formula, we will use the relationship

$$\text{NNP} = C + J + \dot{K} + \dot{K}^f. \qquad [21]$$

Note that environmental spending by government (here J on agri-environmental improvement) is part of NNP, but environmental and resource spending *by firms* (here a on pollution abatement, V on resource discovery and f on resource extraction) is not. This is because by national accounting conventions, firm (as opposed to governmental or household) expenditures are treated as intermediate, and thus *already* excluded from all calculations of national product (whether gross or net, domestic or national) in order to avoid double counting. This convention may be changed for resource discovery costs in the near future (see ONS 1998, §11.25), but it did apply for the time period of this study.

We draw attention to this point of principle because there is some confusion about it in the literature. It is clear in footnote 2 in Hamilton and Atkinson (1996, p677):

> "Most abatement costs are in fact intermediate expenditures in the standard national accounts. This result argues that any expenditures in final demand - by governments, for instance, or the cost of catalytic converters for private automobiles - should be deducted from GNP to arrive at [GNNP]."

Hence, abatement expenditures *by firms* should not be deducted, because they have already been excluded from GNP. However, this qualification was omitted when abatement expenditures were first introduced on p676, and was absent altogether from Hamilton (1996) and Atkinson et al (1997).

3.5 Formulae for augmented GNNP, augmented GS and the value of time

All functional forms are assumed to be as smooth and convex as is needed for present value $W\{\mathbf{C}^*(t)\}$ in expression [3] to converge, and for partial derivatives below (denoted by subscripts) to exist. We still make the heroic assumption that society chooses its control variables, which here are C, $\{a^i\}$, J, $\boldsymbol{D}$, $\boldsymbol{R}^d$, $M{-}X$ and $\boldsymbol{R}^X{-}\boldsymbol{R}^M$, with I then being given by equation [16], to maximise $W(.)$, which means that optimal environmental policies to internalise all externalities are assumed to be in place. We then have:

Proposition 1: Detailed formulae for augmented GNNP and augmented GS

Augmented GNNP: $Y^\dagger = C - \boldsymbol{e}.\boldsymbol{E} + bB + \dot{K} + \dot{K}^f + (\boldsymbol{Q}^R - f_{\boldsymbol{R}}).\dot{\boldsymbol{S}} + Q^t$; [22]

Value of time: $Q^t(t) = \int_t^\infty [F_s + \dot{\boldsymbol{Q}}^R.(\boldsymbol{R}^X - \boldsymbol{R}^M)](s)\, e^{-r(s-t)}\, ds$; [23]

Augmented GS: $\mathbf{Q}^\dagger.\dot{\mathbf{K}}^\dagger = \dot{K} + \dot{K}^f + (\boldsymbol{Q}^R - f_{\boldsymbol{R}}).\dot{\boldsymbol{S}} + Q^t$. [24]

Proof: See Appendix 1.

So if one is willing to predict, or at least use scenarios for, future technical change $\partial F/\partial t$ (denoted F_s in equation [23]), resource price changes $\dot{\boldsymbol{Q}}^R$, and net resource exports $(\boldsymbol{R}^X - \boldsymbol{R}^M)$, then the value of time can be calculated directly using equation [23].

We can use equation [21] to derive alternative expressions for equations [22] and [24] starting from NNP data, which avoid the need for data on net investments $\dot{K}$ and $\dot{K}^f$ when calculating GNNP and GS:

Augmented GNNP: $Y^\dagger = \text{NNP} - \boldsymbol{e}.\boldsymbol{E} + bB - J + (\boldsymbol{Q}^R - f_{\boldsymbol{R}}).\dot{\boldsymbol{S}} + Q^t$; [25]

Augmented GS: $\mathbf{Q}^\dagger.\dot{\mathbf{K}}^\dagger = Y^\dagger - \mathbf{P}.\mathbf{C} = Y^\dagger - (C - \boldsymbol{e}.\boldsymbol{E} + bB)$

$= \text{NNP} - C - J + (\boldsymbol{Q}^R - f_{\boldsymbol{R}}).\dot{\boldsymbol{S}} + Q^t$. [26]

Equation [25] then shows the "top-down" adjustments necessary to reach augmented GNNP when starting from NNP:

- deduct $\boldsymbol{e}.\boldsymbol{E}$, the amenity costs of emissions;
- add the *net* benefit ($bB-J$) of agri-environmental schemes;
- deduct the value $(\boldsymbol{Q}^R-f_{\boldsymbol{R}}).(-\dot{\boldsymbol{S}})$ of rents from depleting resource stocks;
- add the value of time Q^t, which is the present value of $\partial F/\partial t$, exogenous technical progress, plus $\dot{\boldsymbol{Q}}^R.(\boldsymbol{R}^X-\boldsymbol{R}^M)$, the growth in value of net resource.

It is worth clarifying here the effect in equation [25] of our rather arbitrary choice in equation [18] of writing utility as $U(C,\boldsymbol{E},B(J))$ rather than $U(C,\boldsymbol{E},J)$. If we chose the latter, the assumption of optimisation at the margin (used throughout Appendix 1) would replace bB in equation [25] with J, which is then cancelled out by $-J$, leaving no trace of agri-environmental expenditure in augmented GNNP. (The same would happen if we assumed $B = \alpha J$ and optimal expenditure.) Indeed, given the assumption of optimally allocated government spending (no more or less valid for agri-environmental schemes than for health, education, etc), we could just as well write utility as $U(C+J,\boldsymbol{E})$, where J is any government expenditure; and no adjustment for such expenditure then occurs in moving from NNP to augmented GNNP. This theoretical clarification is in fact our primary reason for not including agri-environmental spending J, which is empirically tiny in relation to all other green adjustments made, as a direct determinant of utility in equation [18]. so as to keep it as a separate element of augmented GNNP. This also highlights the choice, discussed next, between using marginal costs or marginal benefits to reflect the value of agri-environmental schemes.

3.6 Choosing from differing marginal environmental valuations in imperfect economies

For completeness, we also mention a major practical difficulty concerning the environmental terms in the national accounting expressions above. The assumption that all externalities have already been optimally internalised, which is required for the above theory to be valid, is patently untrue in practice: all economies have sizeable imperfections. Environmental policies do exist, but no one would expect them to be optimal, partly due to information problems and the absence of market values to price environmental benefits. For example, the marginal benefit of environmental improvement (P^B/P^C or $-P^{Ei}/P^C$, where the latter is also known as the marginal damage cost (MDC) of pollution) is often well above the marginal cost b or e^i. (The exception is when command-and-control regulation of some emissions is too strict, causing marginal benefit to be below marginal cost.) Moreover, in any of these non-optimal cases, it is not just a problem of knowing which marginal cost to use: one also does not know how inaccurate augmented GNNP would be as a present-value-equivalent measure of welfare. (However, as noted above, for government or household environmental expenditures, no choice between marginal cost and marginal benefit may be necessary, since a presumption of optimality can make the expenditures disappear from expressions for augmented GNNP.)

As Hartwick (1990, p296) wrote in the context of externalities caused by open access to renewable resources, "the national accountant faces a no-win choice at this point" between the two marginal values. Hamilton (1996, pp29-30) recognised something similar. Neither author suggested any convention to make choices of marginal benefits versus marginal costs of externalities more consistent. Perhaps it is hard to suggest one when it is unknown even if existing pollution control is too weak or too strong, or which of the two valuation exercises needed is more difficult in practice. On the latter point, Peskin and Delos Angeles (2001, p211) recommend using the marginal benefits rather than marginal costs of environmental improvement, because the former are easier to calculate. However, one may doubt that data difficulties in estimating marginal benefits are any less than for marginal costs, as Peskin and Delos Angeles necessarily assume.

The ideal solution is to use accounting prices (Dasgupta 2001), but given the great difficulties of calculating these, a useful convention for selecting valuations of environmental improvements might be:

(i) if there are data on only marginal benefits or marginal damages, there is no choice, so use what's available;

(ii) if there are data on both benefits and costs, but of very different reliability, use the more reliable data (this may involve considering which of marginal benefits and marginal costs are likely to be more variable across different geographic locations or industrial sectors);

(iii) if there are data on both marginal benefits and costs, which cannot be distinguished on reliability, use the bigger figure. This will be the marginal benefit if, as one often expects, pollution is excessive;

(iv) be explicit about what choices were made, why, and how much difference they make to the final results.

In our case, our use of marginal benefit ($-P^{Ei}/P^{C}$) rather than marginal cost (e^{i}) data for emission abatement is justified by principles (i) or (ii), depending on the pollutant. For agri-environmental expenditure, we use marginal benefits (P^{B}/P^{C}) simply to keep the expenditure visible as a separate item in augmented GNNP.

4. DATA SOURCES USED FOR SCOTLAND

Data were obtained for the calculations from a variety of sources. Input-output (I/O) tables for Scotland from 1992 to 1999 were used as the basis for calculating GDP and emission levels. These tables come from a related research project, not otherwise reported here, to construct a computable general equilibrium, economy-environment model of Scotland which can predict forward values for augmented GNNP and GS under a range of policy scenarios. Because Scotland is in many ways a regional economy, pro-rata procedures based on UK information often had to be adopted, as will be seen. However, the calculations of natural resource rents do not use the I/O tables, but are based on estimates of Scottish natural resource stocks obtained directly from primary sources.

4.1 GDP, GNP, NNP, capital depreciation and the interest rate

GDP data, measuring the value of total income and the value of total output (production), were available from the I/O tables for the Scottish economy, but GNP data were not. To estimate GNP data, we first converted a nominal GDP series taken from the Scottish Executive, checked against annual I/O tables, and converted it into real 1999 prices using HM Treasury's GDP deflator for the UK. We then used the ratio of UK GDP to GNP to further convert the Scottish GDP figures to GNP, thus:

$$\text{GNP(Scot)} \approx [\ \text{GNP(UK)} / \text{GDP(UK)}\ ] \times \text{GDP(Scot)} \qquad [27]$$

GNP data for Scotland were further converted to NNP by deducting estimates of man-made capital depreciation. Since no data exist on depreciation in Scotland, the estimates came from multiplying the UK depreciation ratio ($\delta K/I$) by a series for Gross Domestic Fixed Capital

Formation for Scotland obtained from the I/O tables. This procedure also readily yielded estimates of net investment ($\dot{K}$), thus:

$$\text{NNP(Scot)} = \text{GNP(Scot)} - \delta K\text{(Scot)}, \quad \text{where} \qquad [28]$$

$$\delta K\text{(Scot)} \approx [\ \delta K\text{(UK)} / I\text{(UK)}\ ] \times I\text{(Scot)}, \quad \text{and} \qquad [29]$$

$$\dot{K}\text{(Scot)} = I\text{(Scot)} - \delta K\text{(Scot)}. \qquad [30]$$

Equation [28] was used in equation [25] to calculate augmented GNNP from NNP, while equation [30] was used in equation [24], along with estimates of $\dot{K}^f$ taken from Gibson et al. (1997), to calculate augmented GS.

Two alternative *real interest rates* of 2%/yr and 6%/yr were used. The 2%/yr is an estimate of the UK's real consumption discount rate, from values in HM Treasury (1997) and Pearce (2003) derived, using the Ramsey rule, from the pure time preference rate, long term real growth rates in the UK economy, and the elasticity of the marginal utility of consumption. 6%/yr is the UK Treasury's discount rate for public sector investments.

4.2 Polluting emissions and agrienvironmental spending

To calculate polluting *emissions*, the Scottish economy was broken down into 76 sectors and the pollution attributable to each sector was estimated. We used emission/output ratios for the UK, but then further adjusted estimated Scottish emissions using the ratio of economic activity for each sector between Scotland and the UK. This assumes pollution per unit output is the same between Scotland and the UK for any given sector. This is often not the case: for example, electricity production uses less polluting technologies (proportionately more hydro-electricity) in Scotland. However, no data exist on Scottish-specific emission coefficients for each sector of the economy.

The *marginal damage costs* (MDCs, i.e. the marginal benefits of abatement) of pollutants were taken from a literature review (see Appendix 2). Wherever possible, estimates based on the UK were used, and the studies chosen were those considered to be statistically valid by the EU Environment Directorate. As more than one study existed for all pollutants, an average of the results was used. As noted in Section 3.3, the impacts included in the studies are mainly on health. No real change in MDCs over time was estimated, owing to insufficient data.

There are several *agri-environmental schemes* in Scotland, and the Scottish Executive Environment and Rural Affairs Department gave details of the cost and the area of take-up for each scheme. Schemes included were Environmentally Sensitive Areas, Habitat Scheme, Heather Moorland Scheme, Organic Aid Scheme and the Countryside Protection Scheme. Our money value for the benefits of each hectare came from studies of two Scottish Environmentally Sensitive Areas in Hanley et al (1998).

4.3 Natural resource depletion and growth

For both *coal* and *aggregates*, production data were taken from the UK Minerals Yearbook (various years). The value of UK production was divided by the quantity produced giving a unit value for UK production, which was multiplied by the Scottish production to give Scottish value. The British Geological Survey, authors of the yearbook, suggested that this ex-works value be used as a proxy for price data. Marginal cost data for coal were provided by Scottish Coal. This assumes a constant ratio of values between the UK and Scotland, whilst differences in the proportions of open cast and deep mined coal, or marine- and land-sourced aggregates, cannot be included. Also sand and gravel are the only aggregates included, which may ignore some other aggregates included in the I/O tables.

Fisheries data were obtained from the UK Department for Environment, Food and Rural Affairs (DEFRA). We chose stocks in fishing areas around the Scottish coastline as representing stocks of "Scottish Fish". The values of the fish stocks were taken from the same data source. Nautilus Consulting suggested the marginal cost of fishing be represented by fuel and oil costs (17.5% of value). The fact that there is no such legal entity as a "Scottish fish stock" will effect on the results of this section of the study. Also the way in which the data is presented by DEFRA means that for certain fish species it was necessary to include some of the English Channel in the data.

For *forestry*, the Forestry Commission provided stock figures, prices and marginal costs. Marginal costs were based on an estimated cost of moving logs from the site of felling to the roadside and were assumed to be constant throughout the period.

Data for Scotland’s *oil* stocks and world oil prices (historical and future predictions) were gained from the Energy Information Administration, a branch of the US Department of Environment. These data includes increases in stocks in some years due to technological advances, and new discoveries. Marginal extraction cost data were derived from discussions with individuals in the oil industry. A value of $3.5/barrel was chosen based on costs in the Alba oilfield, being the operational expenditure of a major oil company, adjusted as oil from Alba trades at a discount to much North Sea oil. However, these data are not historical and any changes to the marginal costs are not included in the analysis.

4.4 The value of time (from technical progress and oil price changes)

The *value of time*, Q^t in equation [23], comprises the net present value over an infinite time horizon of two terms: F_t, exogenous technical change in production, and $\dot{\boldsymbol{Q}}^R \boldsymbol{.} (\boldsymbol{R}^X - \boldsymbol{R}^M)$, the value of exogenous resource price changes, weighted by net exports. For our calculations, we truncated the time horizon to 20 years, because forecasts for either term beyond then are very dubious. We have used estimates of total factor productivity (TFP) (i.e. GDP growth not accounted for by increased use of capital and labour) from Senhadji (2000) and Crafts and Mahony (2001) for the UK, to estimate the Scottish TFP growth rate for 1992-1999, and have used this as our estimate of F_t/F to project forward till 2020. This will obviously include both exogenous and endogenous technical progress, but we were not able to distinguish between them for Scotland. We include only one resource price change, that for North Sea Oil, and used British Geological Survey data on past imports and exports of crude petroleum from the UK. Actual data (up to 2001) and price predictions (2001 onwards) were used to calculate changes in price, using the Energy Information Administration predictions noted in Section 4.3. The UK as whole has net exports of about 5m barrels/year of crude petroleum. It was assumed that with 10% of the UK's population, Scotland would export 90% of the remaining production to the rest of the UK. The average of exports in the years 1994-2000 was considered to be a valid estimate of future oil exports from Scotland.

5. RESULTS

5.1 Main results

Our main results are in the first part of **Table 1**. The first part shows annual results for 1992-99 for the constituent parts of green NNP, starting with conventional GNP and ending with the value of time; for augmented GNNP and augmented GS; and then for the change in augmented GNNP, and the interest rate on augmented GS. The change in augmented GNNP from 1992-1993 is shown under 1993 and likewise for later years, so there is no data point for 1992. **Figure 1** plots the augmented GNNP and augmented GS results, and shows clearly how augmented GNNP is always rising and augmented GS is always positive, suggesting no sustainability problems for Scotland during our study period. The positive values of augmented GS are thanks largely to net investment in man-made capital ($\dot{K}$ in equation [24]) being positive and many times bigger than the aggregate depletion of natural capital ($-(\boldsymbol{Q}^R - \boldsymbol{f_R}).\dot{\boldsymbol{S}}$ in equation [24]) that we have been able to measure.

[Table 1 here]

[Figure 1 here]

These results are in contrast to results for roughly similar measures found in Figures 1 and 2 of Hanley et al (1999) for 1980-93. There, Approximate Environmentally-Adjusted National Product (excluding oil discoveries) mainly rose, though not every year; and GS (also excluding discoveries) was always negative. These contrasts can be ascribed mainly to the very different real conditions in the 1980s, when oil was both more expensive and being depleted more rapidly in Scotland; and also to differences in how the various measures have been defined and calculated.

Figure 2 shows the change in augmented GNNP, and the interest rate on augmented GS. These confirm that both measures are consistently positive, so there is indeed no evidence from either indicator of unsustainable development in Scotland during the 1990s.

[Figure 2 here]

Another point, rapidly evident from the last two rows of the first part of Table 1, or from noting that the right and left scales on Figure 2 differ by a factor of 50, is what we will call the *mismatch problem*. *The change in augmented GNNP is for all years much bigger (but by a very variable ratio, between about 6 and 70) than the interest on augmented GS, instead of roughly matching it as predicted by equation [8] from AW's theory.* This rejection of the underlying optimal growth theory is the major, though unexpected result, of our paper. A third obvious point from Table 1 is that, at least according to our data, the mismatch problem will remain no matter how one improves the various "green accounting" adjustments made here, because these adjustments never exceed 7% of conventional NNP.

Before asking what further explanations one might suggest for at least some of the mismatch problem, let us first consider the green terms in our data in more detail. Natural capital is indeed depleted (that is, aggregate resource rents $(\boldsymbol{Q}^R - f_{\boldsymbol{R}}).(-\dot{\boldsymbol{S}})$ are positive) in all but the last year, although forestry stocks are in fact rising throughout. Fish stocks rise in some periods and fall in others; oil production exceeds new discoveries in a few years. Coal and aggregates are always depleted in net terms since we do not count new discoveries for these. Total damage costs of all six pollutants fall over the period from about 8% to about 3% of augmented GNNP, because emissions fall. (Not shown in the table is that SO_2 causes the most damage, followed by PM10.) The net benefits of agri-environmental schemes are positive in all years, but tiny in relation to other elements of augmented GNNP.

As for the augmentation term Q^t, it is always positive, and most of it comprises the value of future growth in production possibilities through technical progress F_t, with a much smaller value due to future oil price rises $\dot{\boldsymbol{Q}}^R$ into the future (the other term in equation [23]). For example, in 1998 the discounted integral of F_t is 86% of the total value of Q^t. This result is, of course, a function of the parameters chosen in this study, and not general.

5.2 Sensitivity tests: can we explain the mismatch problem?

We report here three sensitivity tests, to see how much of the mismatch problem is readily explicable. The first test examines the choice of interest rate, already noted in Section 4.1. The estimated real consumption discount rate of 2% is much lower than the 6% real rate of return on investment in the Scottish economy, because of investment taxes and other distortions. AW's theory, which assumes the two rates are always the same, gives no guidance about which rate is more appropriate for measuring sustainability in an imperfect economy. The results for both rates, which like normal cost-benefit analysis do not allow for the general equilibrium effect that a different interest rate would have on the structure of the economy, are in Table 1. The effect of the interest rate alone can be seen comparing the lower and middle graphs on **Figure 3**. The higher discounting of future changes reduces the value of time Q^t by about 30%,[7] so that augmented GS is lower, but this reduction is greatly outweighed by the tripling of the interest rate when calculating the interest on augmented GS. (Augmented GNNP is barely changed, so no results are given.)

[Figure 3 here]

Another sensitivity test, which will increase the value of the interest on augmented GS in relation to the change in augmented GNNP, is to follow Hamilton and Clemens (1999, p346):

> "The process of calculating genuine savings is, in essence, one of broadening the traditional definition of what constitutes an asset. Perhaps the most important of the additions to the asset base is the knowledge, experience, and skills embodied in a nation's populace, its human capital. The world's nations augment the stock of human capital in large part through their educational systems..."

The current, ultimately arbitrary conventions in national accounting practice treat the vast majority of educational expenditure as consumption, and like Hamilton and Clemens we can reclassify this all as investment in human capital (though a more thorough treatment would allow for capital depreciation through people retiring). Adding investment in human capital to our theoretical model is so simple that a formal treatment is unnecessary. Additions to human capital are all added to augmented GS, but leave augmented GNNP unchanged because they are just reclassifications of expenditure from one component (consumption) to another (investment). We have no exact data on Scottish educational expenditure, so as before we

---

7. It also makes the truncation of the Q^t integral at 20 years more justifiable, since $(1/1.06)^{20} = 0.312$, whereas $(1/1.02)^{20} = 0.673$.

apply the UK ratio (here 4.7%) to Scottish GDP, to produce the figures in the penultimate line of Table 1. These are the same order of magnitude as our previous augmented GS, so the effect is roughly to double our estimate of 6% interest on augmented GS, from the middle to the upper graph in Figure 3.

However, Table 1 shows that even with both of these significant boosts to the interest on augmented GS relative to the change in augmented GNNP, the former is no more than about a fifth of the latter, still far from equal. Further research to explain this remaining gap is clearly a priority, but cannot be pursued here.

A final test was to see how sensitive the results are to variations in the marginal damage costs (MDCs) of pollutants. We calculated augmented GNNP with the lowest or highest MDC values considered to be defensible, instead of the mid-range values chosen for the above calculations. The costs of pollution damage with the low values were about 30-35% lower than with the mid-range values, and about 20-25% higher with the high values. But because of the lower overall weight of the pollution damage costs, as shown in Table 1, in no case was the difference between low-MDC and high-MDC values of augmented GNNP more than 5%; while the differences in the changes in augmented GNNP, which is naturally more volatile, were less than 25%. On this evidence, the precise choice of pollution damage costs is not crucially important when estimating sustainability measures for an industrialised nation, and can do little to solve the mismatch problem.

6. CONCLUSIONS

We have tested here the weak sustainability − strictly speaking to calculate two measures of weak *un*sustainability − of the Scottish economy during 1992-1999 in a way that extends earlier work (Hanley et al 1999) to reflect recent developments in the relevant economic theory. Our main contribution is twofold. For the first time in a real economy, we have simultaneously included the effects of both technical progress and exogenous changes in trade prices (for oil, in this case) in "augmenting" measures of unsustainability. Also for the first time with real data, we have compared two measures which equal each other in a theoretically perfect, present-value-maximising economy (Asheim and Weitzman 2001): the time change in green net national product (GNNP), and the interest on genuine savings (GS). In doing so we faced the inherent difficulty of finding accurate macroeconomic data for a regional economy like Scotland, for which aggregate data like capital depreciation, net property income, exports and imports are not routinely collected, and so must be estimated from other sources. In passing, we also clarified that firms' environmental expenditures (e.g. on pollution abatement) should not be deducted from GNP to compute augmented GNNP, while government environmental expenditures (e.g. on agricultural amenity) should be deducted; and we suggested a convention for choosing between estimates of the marginal costs and benefits of environmental improvement.

To the extent that our data are reliable, our results are clear yet intriguing. Both the change in augmented GNNP and the interest on augmented GS are clearly positive during the period in question, thus giving, by Pezzey and Toman's (2002) tests, no evidence that the Scottish economy was unsustainable then. They are intriguing in that we calculate the change in augmented GNNP to be always many times bigger than the interest on augmented GS, rather than roughly matching it as theoretically should happen. This mismatch problem remains (with a fivefold difference on average) even after making two adjustments which boost the relative size of the interest on augmented GS: using a higher interest rate (the return on investment rather than the consumption discount rate), and reclassifying educational expenditure as investment rather than consumption. Further work could be done on either adjustment, for example by including the effect of retirement on net human capital formation, or by reclassifying some parts of health spending as investment, but our guess is that the mismatch problem will still remain.

Finally, the presence of significant, uninternalised externalities in any real economy casts some doubt on the applicability of AW’s theory, which assumes an optimal (present-value maximising) economy. There are also the well-known practical difficulties of valuing environmental resources, given the very imperfect (or non-existent) markets for such commodities (Dasgupta 2001), and the particular problems of missing data series for a regional economy like Scotland. But the mismatch between the two measures of sustainability is so much greater than could be explained by any of the "green" adjustments made here, that it calls into question some of the more basic assumptions of optimal growth in real economies, and certainly deserves further investigation.

APPENDIX 1: PROOF OF PROPOSITION 1

The current value Hamiltonian of the dynamic optimisation problem of maximising wealth is

$Y^\dagger(t) := Y(t) + Q^t = \mathbf{P}.\mathbf{C} + \mathbf{Q}^\dagger.\dot{\mathbf{K}}^\dagger$ [A1]

where

$\mathbf{K}^\dagger := (K, K^f, \boldsymbol{S}, t)$ is the vector of all state variables; [A2]

$\mathbf{Q}^\dagger := (Q^K, Q^f, Q^{\boldsymbol{S}}, Q^t)$ is the vector of corresponding co-state variables (shadow consumption prices of stocks).

The prices and investment flows defined by equations [12]-[20] then make

$$Y^\dagger(t) = P^C C + \Sigma_i P^{Ei} E^i + P^B B + Q^K \dot{K} + Q^f \dot{K}^f + Q^{\boldsymbol{S}}.\dot{\boldsymbol{S}} + Q^t \qquad [A3]$$

$$= P^C C + \Sigma_i P^{Ei} E^i(\boldsymbol{R}^d, a^i) + P^B B(J)$$

$$+ Q^K \,\mathbf{[}\, F(K, \boldsymbol{R}^d, t) + M - X - \boldsymbol{Q}^R(t).(\boldsymbol{R}^M - \boldsymbol{R}^X) - C - a - J$$

$$- V(\boldsymbol{D}, \boldsymbol{S}) - f(\boldsymbol{R}^d + \boldsymbol{R}^X - \boldsymbol{R}^M, \boldsymbol{S}) - \delta K \,\mathbf{]}$$

$$+ Q^f[rK^f + X - M] + Q^{\boldsymbol{S}}.[\boldsymbol{D} + \boldsymbol{G}(\boldsymbol{S}) - \boldsymbol{R}^d - \boldsymbol{R}^X + \boldsymbol{R}^M] + Q^t \qquad [A4]$$

so the first order conditions with respect to the control variables C, a^i, J, $\boldsymbol{D}$, $\boldsymbol{R}^d$, $M-X$ and $\boldsymbol{R}^X - \boldsymbol{R}^M$ are:

$\partial Y^\dagger/\partial C = P^C - Q^K = 0 \quad \Rightarrow \quad Q^K = P^C$ [A5]

$\partial Y^\dagger/\partial a^i = P^{Ei}(\partial E^i/\partial a^i) - Q^K = 0 \quad \Rightarrow$ (using [19]) $P^{Ei} = -e^i P^C$ [A6]

$\partial Y^\dagger/\partial J = P^B B' - Q^K = 0 \quad \Rightarrow$ (using [20]) $P^B = P^C b$ [A7]

$\partial Y^\dagger/\partial \boldsymbol{D} = -Q^K V_{\boldsymbol{D}} + Q^{\boldsymbol{S}} = \mathbf{0} \quad \Rightarrow \quad Q^{\boldsymbol{S}}/Q^K = V_{\boldsymbol{D}}$ [A8]

$\partial Y^\dagger/\partial \boldsymbol{R}^d = \Sigma_i P^{Ei} E^i_{\boldsymbol{R}} + Q^K(F_{\boldsymbol{R}} - f_{\boldsymbol{R}}) - Q^{\boldsymbol{S}} = \mathbf{0}$ which using [A6] and [A8]

$$\Rightarrow \; -\Sigma_i e^i P^C E^i_{\boldsymbol{R}}/Q^K + F_{\boldsymbol{R}} - f_{\boldsymbol{R}} = Q^{\boldsymbol{S}}/Q^K$$

$$\Rightarrow \; -\Sigma_i e^i E^i_{\boldsymbol{R}} + F_{\boldsymbol{R}} = V_{\boldsymbol{D}} + f_{\boldsymbol{R}} \qquad [A9]$$

$\partial Y^\dagger/\partial(M-X) = Q^K - Q^f = 0 \quad \Rightarrow \quad Q^f = Q^K = P^C$ [A10]

$\partial Y^\dagger/\partial(\boldsymbol{R}^X - \boldsymbol{R}^M) = Q^K(\boldsymbol{Q}^R - f_{\boldsymbol{R}}) - Q^{\boldsymbol{S}} = 0;$ then use [A10], [A8]:

$$Q^{\boldsymbol{S}}/Q^K = \boldsymbol{Q}^R - f_{\boldsymbol{R}} = V_{\boldsymbol{D}} \qquad [A11]$$

Inserting equations [19] and [A6]-[A11] into [A3] then gives

$$Y^\dagger = P^C C - P^C \boldsymbol{e}.\boldsymbol{E} + P^C bB + Q^K(\dot{K} + \dot{K}^f) + Q^{\boldsymbol{S}}.\dot{\boldsymbol{S}} + Q^t \qquad [A12]$$

which using equations [A5], [A8] and [A11] gives

$$= P^C \{ C - \boldsymbol{e}.\boldsymbol{E} + bB + \dot{K} + \dot{K}^f + (\boldsymbol{Q}^R - f_{\boldsymbol{R}}).\dot{\boldsymbol{S}} \} + Q^t \qquad [A13]$$

If the problem is autonomous, time is "unproductive", so its value Q^t, the last term of [22], disappears. If not, first use [A1] and [A4] to get

$$\partial Y/\partial t = Q^K F_t + Q^K \dot{\boldsymbol{Q}}^R.(\boldsymbol{R}^X - \boldsymbol{R}^M)$$

which, after using [A5], [A6] and [A10] becomes

$\partial Y/\partial t = P^C[F_t + \dot{\boldsymbol{Q}}^R.(\boldsymbol{R}^X - \boldsymbol{R}^M)]$, hence from equation [10],

$$Q^t(t) := \int_t^\infty P^C(s)\, [F_s + \dot{\boldsymbol{Q}}^R.(\boldsymbol{R}^X - \boldsymbol{R}^M)](s)\, e^{-r(s-t)}\, ds \qquad [A14]$$

From the Divisia property, $\dot{\mathbf{P}}.\mathbf{C} = \dot{P}^C C + \Sigma \dot{P}^{Ei} E^i + \dot{P}^B B = 0$

[A6] $\Rightarrow P^{Ei} = -e^i P^C \Rightarrow \dot{P}^{Ei} = -e^i \dot{P}^C - \dot{e}^i P^C$

[A7] $\Rightarrow P^B = P^C b \Rightarrow \dot{P}^B = \dot{P}^C b + P^C \dot{b}$

$$\Rightarrow \dot{P}^C(C - \boldsymbol{e}.\boldsymbol{E} + bB) = P^C(\dot{\boldsymbol{e}}.\boldsymbol{E} - \dot{b}B)$$

$$\Rightarrow \dot{P}^C/P^C = (\dot{\boldsymbol{e}}.\boldsymbol{E} - \dot{b}B)/(C - \boldsymbol{e}.\boldsymbol{E} + bB) \qquad [A15]$$

However, in absence of any reliable data, all e^i and b are assumed constant, so from equation [A15], P^C is constant too. Without loss of generality we set $P^C = 1$, so that it disappears, transforming [A13] and [A14] into

$$Y^\dagger = C - \boldsymbol{e}.\boldsymbol{E} + bB + \dot{K} + \dot{K}^f + (\boldsymbol{Q}^R - f_{\boldsymbol{R}}).\dot{\boldsymbol{S}} + Q^t \qquad \text{which is [22];}$$

and $Q^t(t) := \int_t^\infty [F_s + \dot{\boldsymbol{Q}}^R.(\boldsymbol{R}^X - \boldsymbol{R}^M)](s)\, e^{-r(s-t)}\, ds$ which is [23].

APPENDIX 2: ESTIMATES OF MARGINAL DAMAGE COSTS OF POLLUTANTS

For all pollutants considered, we used data for marginal damage costs (MDC) rather than data for marginal abatement costs, because the former were either the only available, or the more reliable data. This follows the convention proposed in Section 3.6. The marginal damage costs were taken from a literature review, with a range of studies used to derive a value for each air pollutant. Wherever possible estimates for the UK were used. For some pollutants such as carbon monoxide and methane, the literature is limited, whilst for carbon dioxide and sulphur dioxide there is a wide literature. The studies chosen were those considered relevant by the European Union (COWI 2000). The pollutants PM10, SO_2 and CO were valued by the ExternE methodology. That is, a linear dose-response function was used to quantify physical effects, and a valuation of years of statistical life lost was estimated. Morbidity costs were based on the cost of hospital stays, emergency visits, restricted activity days, symptom days, asthma attacks and bronchitis attacks (Rabl et al 1998, Maddison 1998 and ETSU 1996). Although only human mortality and morbidity were considered and some impacts were excluded, this technique is considered to be highly relevant for the analysis of these pollutants (COWI 2000).

Data for the three greenhouse gas pollutants (N_2O, CH_4 and CO_2) are from Fankhauser (1995). He used a form of impact pathway looking at temperature damages and is based on global warming potential (which takes account of the durability of each gas in the global atmosphere) as outlined by the IPCC. In the case of CO_2, an aggregation study (Pearce 2003) was also used, and was considered to be representative of the range of results from previous studies.

Where more than one study existed for a pollutant, an average of the results was used. For other pollutants a range of possible values was given, and the average of the bottom and top range was used. **Table 2** shows the values of each pollutant derived from the above studies, and the resulting mid-range value for MDC chosen for our analysis here.

[Table 2 here]

REFERENCES

Asheim, Geir B. (1997). "Adjusting green NNP to measure sustainability." *Scandinavian Journal of Economics*, Vol 99 No 3, 355-370.

Asheim, Geir B. and Martin L. Weitzman (2001). "Does NNP growth indicate welfare improvement?" *Economics Letters*, Vol 73, 233-239. (**AW**)

Atkinson, Giles et al. (1997). *Measuring Sustainable Development: Macroeconomics and the Environment*. Cheltenham, UK: Edward Elgar.

COWI (2000) *A Study on the Economic Valuation of Environmental Externalities from Landfill Disposal and Incineration of Waste, report to EC DG Environment.* Denmark, COWI.

Crafts N., and M. O'Mahony (2001) "A perspective on UK productivity performance." *Fiscal Studies*, Vol 22 No 2, 271-306.

Dasgupta, Partha (2001). "Valuing objects and evaluating policies in imperfect economies." *Economic Journal*, Vol 111 No 471, C1-C29.

ETSU (Energy Technology Support Unit) (1996). *Economic Evaluation of the Draft Incineration Directive*. Report to DG XI of the European Comission. Harwell, UK: ETSU.

Fankhauser, S. (1995). *Valuing Climate Change - The Economics of the Greenhouse*. London: Earthscan publications.

Gibson, Hervey, Geoff Riddington, David Whigham and Jeanie Whyte (1997). *Caledonian Blue Book 1997.* Glasgow, Scotland: Glasgow Caledonian University.

Hamilton, Kirk (1994). "Green adjustments to GDP." *Resources Policy*, Vol 20 No 3, 155-168.

Hamilton, Kirk (1996). "Pollution and pollution abatement in the national accounts." *Review of Income and Wealth*, Vol 42 No 1, 13-33.

Hamilton, Kirk and Giles Atkinson (1996). "Air pollution and green accounts." *Energy Policy*, Vol 24 No 7, 675-684.

Hamilton, Kirk and Michael Clemens (1999). "Genuine savings rates in developing countries." *World Bank Economic Review*, Vol 13 No 2, 333-356.

Hanley, Nick and Giles Atkinson (2003). "Economics and sustainable development: what have we learnt, and what do we still need to learn?" In F. Berkhout, M. Leach and I. Scoones, eds., *Negotiating Environmental Change: New Perspectives from Social Science.* Cheltenham, UK: Edward Elgar.

Hanley, Nick, Douglas MacMillan, Robert. E. Wright, Craig Bullock, Ian Simpson, Dave Parsisson and Bob Crabtree (1998). "Contingent valuation versus choice experiments: estimating the benefits of Environmentally Sensitive Areas in Scotland." *Journal of Agricultural Economics*, Vol 49 No 1, 1-15.

Hanley, Nick, Ian Moffatt, Robin Faichney and Mike Wilson (1999). "Measuring sustainability: a time series of alternative indicators for Scotland." *Ecological Economics*, Vol 28, 55-73.

Hartwick, John M. (1990). "Natural resources, national accounting and economic depreciation." *Journal of Public Economics*, Vol 43, 291-304.

HM Treasury (1997). *Appraisal and evaluation in central government*. London: HMSO.

Maddison, D. (1998). "Valuing changes in life expectancy in England and Wales caused by ambient concentrations of particulate matter." Paper GEC 98-06. London: Centre for Social and Economic Research on the Global Environment, University College London.

ONS (Office for National Statistics) (1998). *United Kingdom National Accounts: Concepts, Sources and Methods*. London: The Stationery Office.

Pearce, David W. (2003). "The social cost of carbon and its policy implications." Forthcoming in *Oxford Review of Economic Policy*.

Pemberton, Malcolm and David Ulph (2001). "Measuring income and measuring sustainability." *Scandinavian Journal of Economics*, Vol 103 No 1, 25-40.

Peskin, Henry M. and Marian S. Delos Angeles (2001). "Accounting for environmental services: contrasting the SEEA and the ENRAP approaches." *Review of Income and Wealth*, Vol 47 No 2, 203-219.

Pezzey, John C. V. (1997). "Sustainability constraints versus ‘optimality’ versus intertemporal concern, and axioms versus data." *Land Economics*, Vol 73 No 4, 448-466.

Pezzey, John C. V. and Michael A. Toman (2002). "Progress and problems in the economics of sustainability". In T. Tietenberg and H. Folmer, eds., *International Yearbook of Environmental and Resource Economics 2002/3*, 165-232. Cheltenham: Edward Elgar. (**PT**)

Rabl, A., J. V. Spadaro and P. D. McGavran (1998). "Health risks of air pollution from incinerators: a perspective." *Waste Management & Research*, Vol 16, 365-388.

Senhadji, A. (2000) "Sources of economic growth: an extensive growth accounting exercise." *IMF Staff Papers*, Vol 47 No 1, 129-157.

Vellinga, Nico and Cees Withagen (1996). "On the concept of green national income." *Oxford Economic Papers*, Vol 48, 499-514.

Vincent, Jeffrey R., Theodore Panayotou and John M. Hartwick (1997). "Resource depletion and sustainability in small open economies." *Journal of Environmental Economics and Management*, Vol 33, 274-286.

Weitzman, Martin L. (1997). "Sustainability and technical progress." *Scandinavian Journal of Economics*, Vol 99 No 1, 1-13.

Table 1 Totals and constituent parts of change in augmented GNNP and interest on augmented GS for Scotland, 1992-1997.
(All values except % are £ million in constant 1999 prices.)

	1992	1993	1994	1995	1996	1997	1998	1999
Main calculation using 2% real interest rate								
Conventional GNP	47946	48982	51685	54221	54592	54637	56533	56897
δK (depreciation of man-made capital)	8340	9301	9460	8385	7568	7496	6934	6863
NNP = GNP − δK	39606	39680	42225	45836	47024	47140	49599	50034
$\boldsymbol{e}.\boldsymbol{E}$ = pollution damage	3096	2906	2615	2444	2290	2097	2108	1712
$bB{-}J$ = net benefit of agri-envt. schemes	1	1	2	3	3	2	4	4
$(\boldsymbol{Q}^R{-}f_R).\dot{\boldsymbol{S}}$ = negative resource rents	-293	-184	-87	-233	-199	-164	-81	109
Q^t = value of time	716	682	690	609	609	621	675	752
Augmented GNNP = NNP − $\boldsymbol{e}.\boldsymbol{E}$ + $bB{-}J$ + $(\boldsymbol{Q}^R{-}f_R).\dot{\boldsymbol{S}}$ + Q^t	36934	37273	40214	43771	45146	45502	48089	49186
Aug. GNNP / NNP	93%	94%	95%	95%	96%	97%	97%	98%
Augmented genuine savings (GS)	1943	1651	2155	2507	2492	2791	3625	3664
Change in aug. GNNP	–	339	2942	3557	1375	356	2587	1098
Int. rate r × aug. GS	39	33	43	50	50	56	73	73

Sensitivity testing by using 6% real interest rate; then adding educational expenditure								
Q^t = value of time	519	488	498	419	418	429	482	561
Change in aug. GNNP	–	342	2944	3559	1374	355	2586	1099
Int. rate r × aug. GS	105	87	118	139	138	156	206	208
Estimated educational expenditure	2579	2646	2776	2899	2908	2903	2991	3010
Interest rate r × aug. GS including educ. expenditure	259	246	284	313	313	330	385	389

Table 2: Estimates of marginal damage costs of pollutants

Pollutant	Original value(s) in £/tonne	Year, original currency	Adjustment factor to 1999 prices	Value(s) in 1999 £/tonne	MDC used in 1999 £/tonne
SO_2	4940	1996, euro	1.25	6175	
	4500	2000, euro	1.64	7380	
	6089	1998, £	1.024	6235	6597
PM10	30500	1996, euro	1.25	38125	
	20000	1997, £	1.053	21060	
	3874	1998, £	1.024	3967	21051
N_20	380-3420	1997, £	1.053	400-3601	2001
CO	2	1998, euro	1.48	3	
	7	1993, ecu	1.28	9	6
CH_4	35-150	1997, £	1.053	37-158	97
CO_2	1.2-9	1997, £	1.053	1.3-9.5	
	3-6	2002, £	0.96	2.9-5.8	5

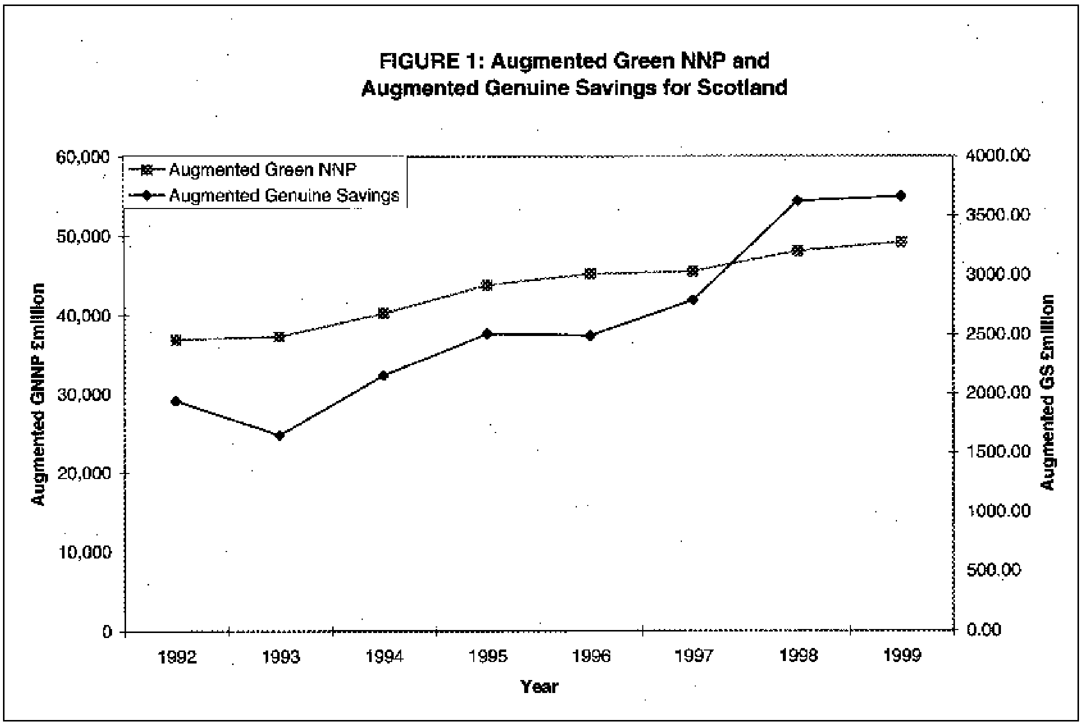
FIGURE 1: Augmented Green NNP and
Augmented Genuine Savings for Scotland
Augmented Green NNP
Augmented Genuine Savings
Augmented GNNP £million
Augmented GS £million
60,000
50,000
40,000
30,000
20,000
10,000
0
4000.00
3500.00
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
1992
1993
1994
1995
1996
1997
1998
1999
Year

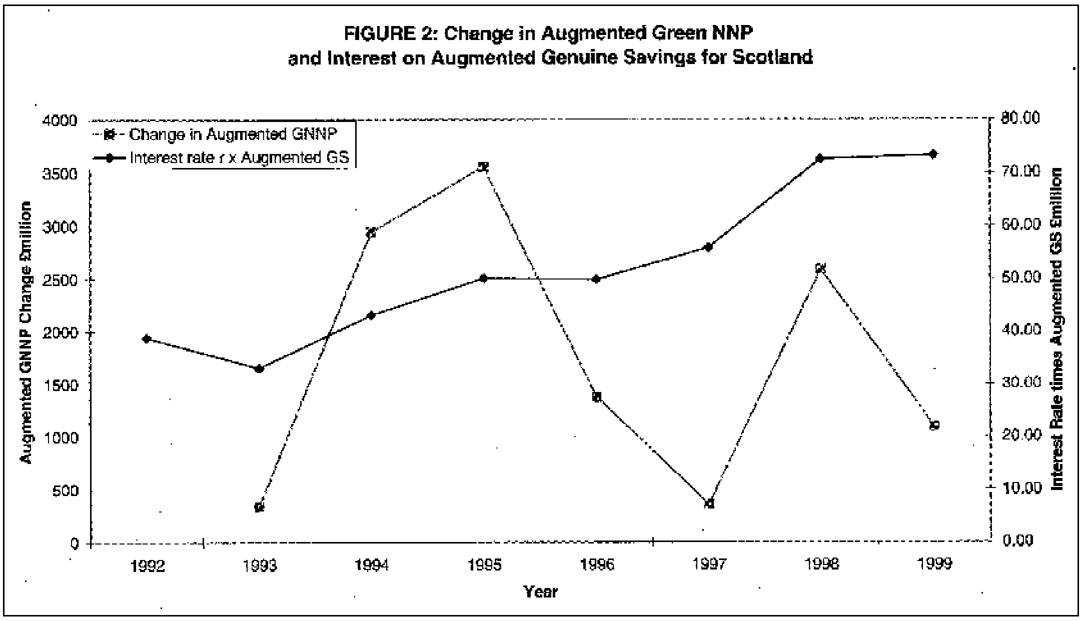
FIGURE 2: Change in Augmented Green NNP
and Interest on Augmented Genuine Savings for Scotland
Change in Augmented GNNP
Interest rate r x Augmented GS
Augmented GNNP Change £million
Interest Rate times Augmented GS £million
4000
3500
3000
2500
2000
1500
1000
500
0
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
1992
1993
1994
1995
1996
1997
1998
1999
Year

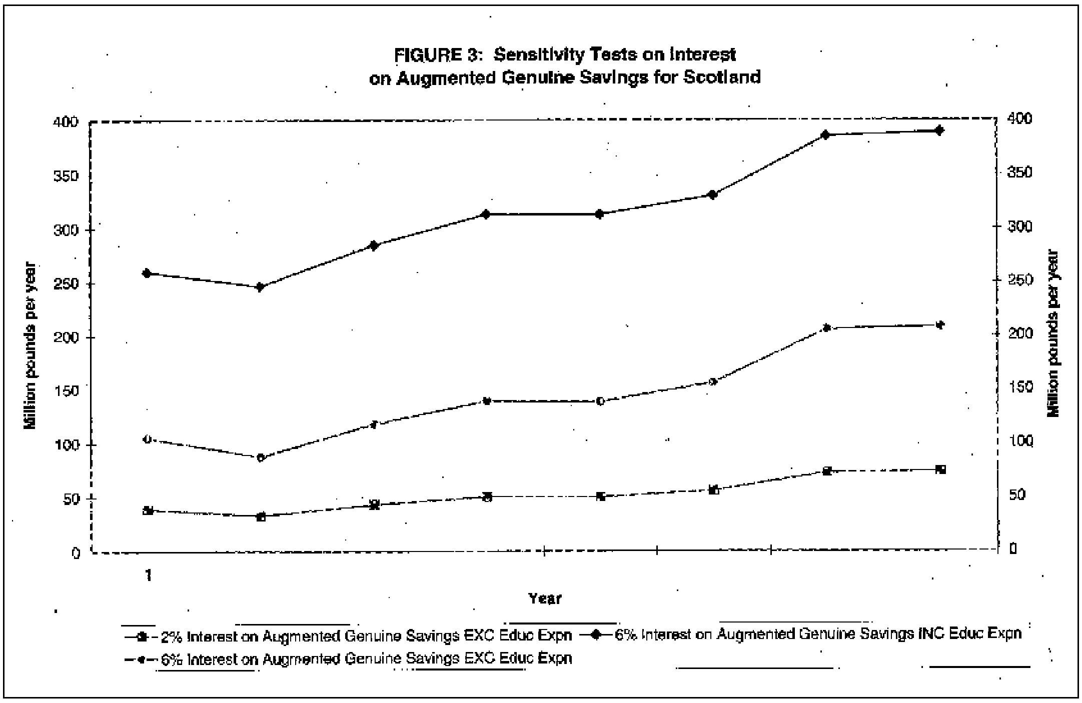
FIGURE 3: Sensitivity Tests on Interest
on Augmented Genuine Savings for Scotland
Million pounds per year
Million pounds per year
400
350
300
250
200
150
100
50
0
1
Year
2% Interest on Augmented Genuine Savings EXC Educ Expn
6% Interest on Augmented Genuine Savings INC Educ Expn
6% Interest on Augmented Genuine Savings EXC Educ Expn