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Measuring Sustainability in the UN System of Environmental-Economic Accounting

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Abstract The adoption of the *System of Environmental-Economic Accounting 2012: Central Framework* as a UN statistical standard is a landmark in environmental accounting. The SEEA has the same authority and weight as the System of National Accounts in the pantheon of official statistics. The SEEA defines the unit value of depletion of an exhaustible resource to equal the average unit value of the asset (the total asset value divided by the physical stock of resource). By applying this definition to a non-optimal Dasgupta–Heal–Solow model of an extractive economy, we show that 'depletion-adjusted net saving' as defined in the SEEA supports a generalized version of the Hartwick Rule. This measure of saving can guide policies for sustainable development in extractive economies, in particular fiscal policies concerning consumption and investment expenditures funded by resource rents. The conditions required to support this finding are (i) that extraction declines over time at a constant rate, and (ii) that the marginal cost of resource extraction is constant. A less general result holds in the case of increasing marginal extraction costs.

Keywords Sustainable development · Exhaustible resources · Depletion · Environmental accounting · Hartwick Rule

JEL Classification Q32 · Q36

1 Introduction

When the *System of Environmental-Economic Accounting 2012: Central Framework* (SEEA 2012) was adopted as a UN statistical standard, it set the stage for much wider adoption of resource and environmental accounting by countries across the world. This paper explores

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the extent to which the new standard can be used to measure the sustainability of development in extractive economies and, more broadly, to underpin policies for achieving sustainability.

There is by now a very large literature on the economics of sustainable development, as the *Handbook of Sustainable Development* (Atkinson et al. 2014) attests. Within this literature a key question is whether wellbeing can be sustained in a world of finite resources. Solow (1974) boiled the problem down to its essentials by considering a simple economy with constant population, fixed technology, produced capital that does not depreciate, and a finite exhaustible resource that is necessary for production. He concludes that constant consumption is feasible in this economy if investment is a linear function of time, and the elasticity of substitution between the two assets is equal to 1. Dasgupta and Heal (1979) used this model economy to develop their pioneering book on the economics of exhaustible resources. The subsequent literature on sustainability has expanded the basic Solow model to embrace issues such as renewable resources, growing population, endogenous versus exogenous technical change, openness to trade, exogenous world prices, and pollution externalities.

Hartwick (1977) showed that underpinning the Solow (1974) result is a simple policy rule. The Hartwick Rule states that if investment just equals the scarcity rent on resource extraction, then consumption will be constant. Investment in produced capital just offsets the depletion of the resource. If this rule is applied at each point in time, then consumption can be sustained. This result rests upon the basic assumptions of Solow.[1] Hamilton and Hartwick (2005) and Hamilton and Withagen (2007) generalize this result to multiple consumption goods and multiple assets, showing that consumption and wellbeing will rise if 'genuine saving'—net saving including the depletion of natural resources and pollution damages—is positive and growing at a rate less than the interest rate for the economy.[2] The more general relationship between an adjusted measure of net saving and the change in social welfare (the present value of future wellbeing) was established in Hamilton and Clemens (1999), Dasgupta and Mäler (2000), and Asheim and Weitzman (2001).

While Pezzey (1989) defined a development path for an economy to be sustainable if current utility does not decrease at any point along the path, Dasgupta and Mäler (2000) use a less stringent condition, that a path is sustainable if social welfare (the present value of utility) does not decline at any point along the path. In this paper we adopt the Dasgupta–Mäler definition.[3]

The theory cited above shows that there is a fundamental link between measuring sustainability and national accounting. The link is provided by the measure of net saving adjusted for resource depletion in extractive economies. While this theoretical work progressed, there was a parallel stream of work on what might be termed 'practical wealth accounting': national accounts have been extended by including experimental stock and flow accounts for a variety of natural resources. Ahmad et al. (1989) is an early introduction to this literature. This

[1] Note that Solow (1974), Hartwick (1977) and Dasgupta and Heal (1979) all assume that produced capital does not depreciate at a fixed rate. The reason is that, with a wasting asset, produced capital must grow without bound in order to offset declining resource inputs to production. With a neoclassical production function this implies that the marginal product of capital must also approach 0. The result is that the effective interest rate (the marginal product of capital minus the fixed depreciation rate) will turn negative in finite time as the resource is depleted. The 'solution' to this problem is endogenous technical change; exogenous technical change effectively makes the sustainability problem disappear. The comments of two anonymous reviewers are acknowledged with thanks. The usual caveats apply.

[2] The intuition behind this finding is discussed in Sect. 3.

[3] Consider an economy that is recovering from a major disaster—in the short run consumption will decline in order to finance investment in reconstruction. By the Pezzey (1989) definition this economy is unsustainable owing to declining consumption. If the initial period of declining consumption is finite, then social welfare will increase at each point in time if the rate of time preference is sufficiently low—the economy will be sustainable by the Dasgupta and Mäler (2000) definition.

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work has been supported by the efforts of the United Nations Statistical Commission to develop concepts, classifications and methodology to underpin resource and environmental accounting. The culmination of this work by official statisticians is the UN *System of Environmental-Economic Accounts 2012: Central Framework* (SEEA 2012).

The adoption of the SEEA is a landmark because it establishes a UN statistical standard for resource accounting that has the same authority and weight as the System of National Accounts (SNA). UN standards ensure international comparability and provide essential methodological guidance. For a specialized topic such as environment and resource accounting, it is likely that countries will use the SEEA to develop accounts according to their policy needs and technical capacity. World Bank (2011, Ch 8) lists 20 developed and developing countries where effort has gone into natural resource accounting prior to the publication of the SEEA.

The SEEA establishes two new national accounting aggregates: depletion-adjusted net saving, and depletion-adjusted national income. The body of economic theory suggests that depletion-adjusted net saving could be used to guide real-world policies for sustainable development, by implementing the Hartwick Rule and its generalizations. This would be particularly important in developing countries with large extractive industry sectors—in these countries resource depletion can equal 10–50 % or more of GDP (see *World Development Indicators 2014* figures for Adjusted Net Saving).

This paper focuses on the SEEA's treatment of exhaustible resources and assesses whether accounting aggregates such as depletion-adjusted net saving defined in the SEEA can serve as indicators of sustainability. We find that, under fairly weak conditions, the generalized Hartwick Rule holds in a non-optimal DHS economy where resource depletion is measured using SEEA methods.

We explore the application of SEEA principles to a model Dasgupta–Heal–Solow (DHS) economy, since this reduces the sustainability question to its core. As noted, the DHS model represents a closed economy with an exhaustible resource where production is impossible without resource inputs; technology is fixed, with no technical progress; produced capital does not depreciate; and population is constant. We do not assume optimality, where a social planner maximizes social welfare.[4]

Finally, it is important to clarify how the current paper extends Hamilton and Ruta (2009). Hamilton and Ruta calculate the accounting price for resource extraction in a DHS economy—the marginal contribution of a unit of resource to total wealth (based upon Dasgupta and Mäler 2000). They assume a fixed exhaustion time and that both resource extraction and unit resource rents are constant over time. Hamilton and Ruta show that the accounting price is less than the change in total wealth when a unit of resource is extracted, and present some empirical examples. This result accords with their findings in models of an optimal extractive economy. But they do not show that the Hartwick Rule will yield constant consumption if net investment is calculated using their derived value of depletion.[5] The current paper fills this gap.

[4] Dasgupta and Heal (1979) famously show that the optimal policy for this economy—the policy that maximizes social welfare—leads to a path for consumption that falls asymptotically to zero. Optimality requires two dynamic conditions to hold: the Ramsey Rule, which equates the cost of deferring a unit of consumption to the interest rate defined by the marginal product of capital; and the Hotelling Rule, which assures that marginal resource rents rise at the rate of interest. The sustainability results of Solow (1974) and Hartwick (1977) require the Hotelling Rule to apply, but not the Ramsey Rule.

[5] Wei (2015) shows that a slightly different parameterization of the model of Hamilton and Ruta (2009) leads to an accounting price for natural resources that is equal to the change in total wealth per unit of resource extracted. But he does not show whether this measure of depletion can lead to constant consumption under the Hartwick Rule. Section 2 turns to this question.

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Section 2 develops the basic framework for a non-optimal extractive economy with an 'allocation mechanism,' based on Dasgupta and Mäler (2000), and shows that assuming that the change in total value of the resource asset is equal to the value of depletion would necessarily lead to declining wellbeing if the Hartwick Rule were based upon this measure. Section 3 establishes the main result, showing that the generalized Hartwick Rule holds, subject to two basic conditions, when the SEEA's suggested methodology for valuing depletion is applied. Section 4 examines the dynamics of the unit value of depletion in the SEEA, and gives some empirical insight into the measure.

The final section concludes and discusses policy applications.

2 Defining the Allocation Mechanism and an Example Application

Our goal in this section is to flesh out the concept of an allocation mechanism for a non-optimal Dasgupta–Heal–Solow (DHS) economy, and then to measure wellbeing over time under a particular savings rule: set saving equal to the change in total resource wealth.

The DHS economy is the canonical example of a simple economy where unsustainability is a potential development outcome. The economy is closed to trade, and therefore domestic saving equals domestic investment. It exploits a finite stock of a natural resource, resource extraction is costless, produced capital does not depreciate, and there is no technical progress.

The economy has production function $F(K, R)$ which satisfies the usual neoclassical conditions,

$$F_K > 0, \quad F_R > 0, \quad F_{KK} < 0, \quad F_{RR} < 0, \quad F_{KR} > 0, \quad F_{RK} > 0 \tag{1}$$

Here K is the stock of produced capital, while R is the flow of resource extraction. Capital and resources are necessary for production, in the sense that $F(K, 0) = F(0, R) = 0$. All variables are assumed to be functions of time, unless otherwise specified. Production of a homogeneous good is either consumed (C) or invested,

$$F(K, R) = C + \dot{K} \tag{2}$$

Utility is a function of consumption only, so $U = U(C)$. The pure rate of time preference ρ is constant. F_R is the price for units of the resource R, and F_K is the interest rate for the economy. Resource extraction is costless, and so $F_R R$ measures both marginal and total resource rents. Extraction of the resource decreases the resource stock S,

$$\dot{S} = -R \tag{3}$$

Because $F_R > 0$, resource extraction is profitable by definition.The stock S therefore represents the proven reserve of the resource.

The *allocation mechanism* α for this economy has the following characteristics:[6]

(i) There is an extraction rule that determines the path $\{R\}$ for resource extraction.
(ii) There is an investment rule that defines the path for investment $\{\dot{K}\}$, and therefore implicitly defines the path for consumption $\{C\}$ as well.

[6] In Dasgupta and Mäler (2000) the concept of an allocation mechanism is very general. It is essentially a program or set of rules that defines a unique future path for the economy, taking initial stocks as given. While conceived as a way to parameterize a non-optimal economy (one which does not maximize social welfare), optimal development paths can be considered to be underpinned by specific allocation mechanisms which ensure that the Ramsey Rule, for example, holds at each point in time.

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(iii) The development path defined by α is feasible, so that

$$K > 0, \; S > 0 \; \forall \, t. \tag{4}$$

With these definitions in hand, we define social welfare V for this economy as,

$$V = \int_t^{\infty} U\left(C\left(z\right)\right) e^{-\rho(z-t)} dz \tag{5}$$

Because the pure rate of time preference is constant, integrating by parts yields,

$$\dot{V} = \int_t^{\infty} \dot{U} e^{-\rho(z-t)} dz = \int_t^{\infty} U_C \dot{C}\left(z\right) \cdot e^{-\rho(z-t)} dz \tag{6}$$

The change in social welfare equals the discounted integral of the marginal utility of consumption times the instantaneous change in consumption. With this as the general setting for a DHS economy subject to the allocation mechanism α, we now turn to a specific instance.

2.1 An Example Saving Rule as an Allocation Mechanism

We present a non-optimal infinite horizon economy where the investment rule is to set investment equal to the change in total resource wealth which results from resource extraction. This investment rule is a particular case of the Hartwick Rule, substituting the change in total resource wealth for total scarcity rents as derived in Hartwick (1977). As Hamilton and Ruta (2009) discuss, this is an important case to consider because much of the resource accounting literature prior to SEEA (2012) assumed that the change in total resource wealth was the appropriate way to value resource depletion.

We modify expression (2) to allow for costly extraction, $f\left(R\right) > 0$:

$$F\left(K, R\right) = C + \dot{K} + f(R) \tag{7}$$

The value of the resource equals the present value of total rents,

$$N = \int_t^{\infty} \left(F_R(z) R\left(z\right) - f\left(R\left(z\right)\right) \cdot e^{-\int_t^z F_K(\tau) d\tau} dz \tag{8}$$

It follows that the total change in the value of the resource stock (as a result of extraction) is equal to the return on the resource asset minus the resource rents on extraction,

$$\dot{N} = F_K N - \left(F_R R - f\left(R\right)\right)$$

We define the allocation rules for extraction and investment constituting α to be:

$$\dot{R} < 0 \; \forall t \tag{9}$$

$$\dot{K} = -\dot{N} \; \forall t \tag{10}$$

Over the infinite time horizon this economy is feasible ($S\left(t\right) > 0 \; \forall t$) only if the quantity depleted R is non-decreasing over, at most, finite periods of time—expression (9) ensures that this holds true. It is straightforward to show that $\dot{N} < 0$ when quantity R is extracted, hence the sign in expression (10). Expression (10) is a 'Hartwick-type' rule for this economy. The Hotelling and Ramsey rules are not assumed to hold.

The instantaneous change in investment is given by,

$$\ddot{K} = -\ddot{N} = -\frac{d}{dt}\left(F_K N - F_R R + f\left(R\right)\right) = -\left(\dot{F}_K N - F_K \dot{K} - \dot{F}_R R - F_R \dot{R} + f' \dot{R}\right)$$

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The change in consumption is therefore given by,

$$\dot{C} = F_K \dot{K} + F_R \dot{R} - f' \dot{R} - \ddot{K} = \dot{F}_K N - \dot{F}_R R \tag{11}$$

Since $\dot{F}_K = F_{KK}\dot{K} + F_{KR}\dot{R}$ and $\dot{F}_R = F_{RR}\dot{R} + F_{RK}\dot{K}$, it follows from expression (1) and the allocation rules (9) and (10) that $\dot{C} < 0 \; \forall t$. From expression (6) it follows that social welfare is declining at each point in time. Investing an amount precisely equal to the total change in the value of the resource stock $(-\dot{N})$ is a policy rule for unsustainability in this non-optimal economy.

Note that this result is driven by declining marginal returns in the production function. In principle you could have an economy where the resource is not used in production and resource rents are invested in a financial asset that yields a fixed rate of return. This economy could be sustainable owing to the existence of this fixed rate—in fact, this is how El Serafy (1989) sets up the problem of measuring resource depletion. But if the economy as a whole is subject to declining marginal returns on produced capital, it is hard to see how the financial asset could have a fixed yield forever.

This result is useful because, as noted, Hamilton and Ruta (2009) argue that much of the literature on 'green accounting' for exhaustible resources prior to the adoption of the SEEA (2012) assumed that the correct value of resource depletion is the change in the total value of the resource stock. This was the recommendation of the earlier draft UN standard (SEEA 2003, Box 7.3). A naïve application of the Hartwick Rule—set investment in produced capital equal to the value of resource depletion measured on this basis—would actually lead to unsustainability.[7]

3 The Generalized Hartwick Rule and the SEEA

We now turn to our central question: can depletion adjusted net saving, as defined in the SEEA, underpin a policy rule for sustainability in a non-optimal economy? To explore this we need to define a saving rule and an extraction rule in the non-optimal DHS economy.

As theory suggests, the SEEA assumes that the value of the exhaustible resource stock S is equal to the present value of total resource rents on extraction, N. The SEEA then defines the unit value of the resource in the ground as p, where

$$p \equiv \frac{N}{S}$$

This is the average asset value per unit of resource. For resource extraction is R, expression (3) defines the change in the resource stock, $\dot{S} = -R$. The value of resource depletion is then defined in the SEEA to be,

$$\text{Depletion} = -pR$$

Here the SEEA makes a conceptual leap by assuming that the unit asset value p is the appropriate way to value depletion. While economists would generally expect depletion to be valued at the margin, we show below that the SEEA value of depletion can support a sustainability rule.

[7] El Serafy (1989) made an important contribution by showing that the total rent on resource extraction can be partitioned into an income component and a capital consumption component. This builds on notions of Hicksian income and the Permanent Income Hypothesis. However, his formula for valuing resource depletion is equivalent to measuring the change in the total value of the resource stock which, as established in expression (11), leads to unsustainability.

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Hamilton and Hartwick (2005) establish that a generalization of the Hartwick Rule for sustainability holds in the optimal DHS economy. To derive this result they do not require full optimization of the economy—they simply require dynamically efficient pricing of the resource, i.e. the Hotelling Rule. Hamilton and Hartwick derive the following basic relationship between genuine saving and changes in consumption:

$$\dot{C} = F_K G - \dot{G} \tag{12}$$

The standard Hartwick Rule follows by assuming that $G = 0$ at each point in time in expression (12)—this results in a constant level of consumption over time. But a more general rule for sustainability based on expression (12) can be derived by choosing $G > 0$ and $\frac{\dot{G}}{G} < F_K$. If this rule is applied at each point in time, consumption will be everywhere increasing in the DHS economy.

The intuition behind expression (12) can be seen by first assuming that $G > 0$ is constant. In this case $\dot{C} = F_K G$—the increment to consumption is just equal to the return on net saving. If G is increasing then, other things being equal, this will entail less consumption and more investment. The result is what we see in expression (12). The change in consumption is equal to the difference between these countervailing effects.

The central result that we wish to establish is that expression (12) can be derived in a non-optimal DHS economy with costly extraction $f(R)$ where:

$$F(K, R) = C + \dot{K} + f(R), \text{ and}$$

(i) the extraction cost function exhibits constant marginal cost, $f(R) = \gamma R$, for constant γ
(ii) genuine saving is measured as $G = \dot{K} - pR$, with $p \equiv \frac{N}{S}$ per the SEEA methodology, and
(iii) the extraction rule is $\frac{R}{S} = \phi$ for constant $\phi < 1$.

Over an infinite extraction horizon starting at time t we define $\phi = \frac{R(t)}{S(t)}$. Given $S(t)$, this extraction rule defines $R(t)$ and ensures that $S(t) = \int_t^\infty R(z)\,dz$.

The extraction rule also implies that $\frac{\dot{S}}{S} = \frac{\dot{R}}{R} = -\phi$, and that $G = \dot{K} - \phi N$.

The value of the resource asset is the present value of total rents over the infinite horizon,

$$N = \int_t^\infty (F_R(z) - \gamma) \cdot R(z) \cdot e^{-\int_t^z F_K(\tau)d\tau} dz$$

Now,

$$\begin{aligned} \ddot{K} &= \dot{F} - \dot{C} - f'\dot{R} = F_K \dot{K} + (F_R - \gamma)\dot{R} - \dot{C} \\ \dot{G} &= \ddot{K} - \phi \dot{N} = F_K \dot{K} + (F_R - \gamma)\dot{R} - \dot{C} - F_K \phi N + \phi(F_R - \gamma)R \end{aligned} \tag{13}$$

and therefore,

$$F_K G - \dot{G} = \dot{C} - (F_R - \gamma)\dot{R} - \phi(F_R - \gamma)R = \dot{C} \tag{14}$$

If genuine saving G is measured using the SEEA methodology to value resource depletion, marginal extraction costs are constant, and resource extraction R is a constant fraction of the resource stock S, then as long as $G > 0$ and G is growing more slowly than the interest rate, consumption will be rising. If this saving rule applies at each point in time, then from expression (6) it follows that social welfare is everywhere rising. The economy is sustainable.

If marginal extraction costs are not constant, then the average rent per unit of resource $F_R - \frac{f(R)}{R}$ will differ from the marginal rent per unit of resource $F_R - f'$, and expression (14) becomes,

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$$F_K G - \dot{G} = \dot{C} - \phi \left(f' R - f(R) \right) \tag{14a}$$

Since the assumption of constant marginal extraction costs is restrictive, a plausible alternative is to assume that marginal extraction costs are increasing. The final term in expression (14a) will be positive in this case.

From expression (14a) we therefore conclude that if marginal extraction costs are increasing in R, then consumption will be increasing as long as genuine saving is non-negative and growing at a rate less than the interest rate. If genuine saving is negative and falling at a rate less than the interest rate, then consumption will be falling only if $F_K G - \dot{G}$ is *sufficiently* negative.

If the extraction cost function is isoelastic with elasticity $\epsilon > 1$ then there will be increasing marginal extraction costs[8] and the final term in expression (14a) reduces to $\phi(\epsilon - 1) f(R)$. For measured values of G and $\dot{G}$ it is therefore possible to assess how large ϵ would have to be in order to lead to growing consumption—this assumes that total extraction costs can be measured but ϵ is unknown.

Finally, it is worth considering the case where the extraction cost function exhibits stock effects. Denote cumulative extraction as $Z(t) = S(0) - S(t)$, and assume that $f = f(R, Z)$. If $f_Z > 0$, this could represent decreasing quality of the resource stock as extraction proceeds. If $f_Z < 0$, this could represent learning as a result of extraction—the producer learns from the extraction process and is able to decrease costs as a result.[9] Expression (14b) shows the resulting expression when stock effects matter,

$$F_K G - \dot{G} = \dot{C} - \phi \left(f_R R - f(R, Z) \right) + F_Z R \tag{14b}$$

If there is learning from extraction, $f_Z < 0$, then the result is qualitatively the same as for expression (14a). If stock effects increase extraction costs, $f_Z > 0$, then the sign of $\dot{C}$ will depend on empirical estimates of the cost function when genuine saving is equal to 0.

To summarize, we have established that depletion-adjusted net saving, measured in a DHS economy using SEEA definitions, will support the generalized Hartwick Rule if (i) resource extraction declines at a constant rate, and (ii) marginal extraction costs are constant. If marginal extraction costs are increasing or stock effects exist then the result is less general when trying to assess whether an economy is on an unsustainable path.

This result is derived for an infinite horizon problem, but it transfers directly to an economy where the resource is exhausted over a finite period $T - t$. Obviously resources cannot be a necessary input to production in such an economy, and the allocation rules for the economy must have two phases—one for the period of resource production, which will mirror what we just presented, and one for the remaining period. To ensure resource exhaustion over the finite period, the main parameters of the extraction program must satisfy,

$$S(t) = \int_t^{T-t} R^*(t) \cdot e^{-\phi(z-t)} dz \tag{15}$$

Here, if $R(t)$ is the currently observed quantity of resource extracted, we can choose $\phi = \frac{R(t)}{S(t)}$ and $T - t = \frac{1}{\phi}$, for example. Then $R^*(t)$ can be chosen to satisfy expression (15).

[8] Morovati Sharifabadi (2013) estimates the elasticity of the (conventional) oil extraction cost function in Texas to be $\epsilon = 4.08$ in 2006.

[9] These assumptions parallel those in Arrow et al. (2003) for a resource discovery function.

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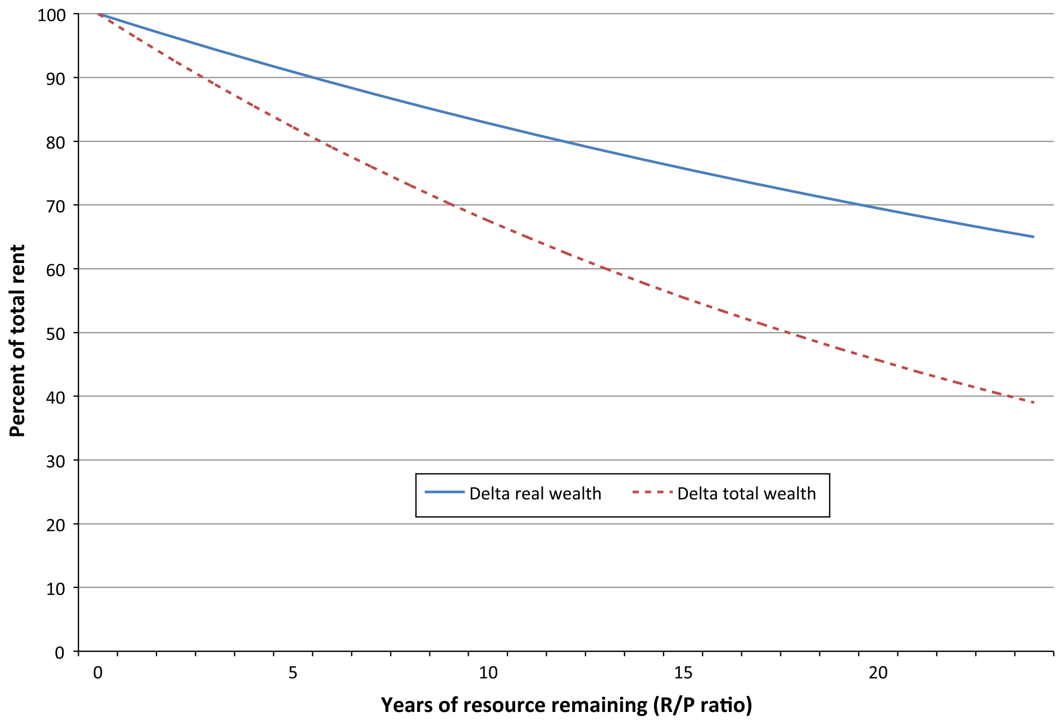

Fig. 1 Changes in total and real wealth as a function of resource lifetime. *Source*: author's calculations; discount rate is 4 %

4 Level and Dynamics of the Unit Value of Depletion in the SEEA

Finally, to deepen our understanding of applying the SEEA methodology in the DHS economy, we examine two further issues: what is the rate of change of the unit value of depletion p, and is the value of depletion generally less than total rents on extraction? The derivation below assumes that marginal extraction costs are constant.

Since we know that marginal rents rise at the rate of interest in the optimal DHS economy, it is worth exploring how the unit value of depletion p behaves in the non-optimal economy. Since $p = \frac{N}{S}$, we can derive the following when resource extraction falls at rate ϕ:

$$\frac{\dot{p}}{p} = \frac{\dot{N}}{N} - \frac{\dot{S}}{S} = \phi + \frac{F_K N - (F_R - \gamma)R}{N} = F_K + \phi\left(1 - \frac{(F_R - \gamma)\,S}{N}\right) \tag{16}$$

We know from the theory of the mine that the value of the mine, N, is maximized when the marginal rental rate $F_R - \gamma$ grows at the rate of interest—this is just the Hotelling Rule. In this instance the maximum value of the mine is given by $(F_R - \gamma)S$, because the growth rate and the discount rate cancel. The value of the non-optimal mine N is necessarily less than $(F_R - \gamma)S$, and so the term in parentheses is negative, implying that the growth rate of the unit value of depletion is less than the interest rate.[10]

For a finite extraction program where resource deposits have lifetimes up to 25 years, Fig. 1 plots the unit value of depletion (the change in real wealth using the SEEA methodology) and the change in total wealth as a percent of total rent on extraction. The curves plotted assume

[10] Note, however, that by construction N will approach $(F_R - \gamma)\,S$ as the mine nears depletion, so the growth rate of p will approach the discount rate. The Hotelling Rule is approached asymptotically, but it is important not to over-emphasize this point: Livernois (2009) finds virtually no evidence for the Hotelling rule actually being observed in resource markets.

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a constant unit rent (average rent per unit of resource) and a constant quantity extracted in each period. The assumed discount rate is 4 %. The two curves are defined as:

$$\text{Delta real wealth} = -p\dot{S} = p\bar{R}$$
$$\text{Delta total wealth} = -\left(p\dot{S} + \dot{p}S\right)$$

The difference between the two curves in Fig. 1 is therefore equal to the capital gains ($\dot{p}S$) when quantity $\bar{R}$ is extracted, expressed as a share of total rent on extraction.[11] The difference increases as the resource deposit size increases. At 25 years of reserves, the change in real wealth when the resource is extracted is equal to 65 % of total rents—this compares with the change in total wealth, amounting to 39 % of total rent. As we saw in Sect. 2 of this paper, setting investment equal to the change in total resource wealth results in declining social welfare.

With regard to the level of resource depletion compared to the total rents on extraction, Fig. 1 shows that depletion is always less than total rent under the assumption of constant unit rents and constant extraction. More generally, going back to the optimal mine, we know that N is maximized if marginal rents follow the Hotelling Rule. As argued above, this implies that $N = (F_R - \gamma)S$ for optimal extraction. In general, N will be lower than this in the non-optimal economy, implying that,

$$pR = \frac{N}{S}R < (F_R - \gamma)R$$

The right-hand side of this expression equals the total rent on extraction. In general, therefore, the value of resource depletion will be less than total rent in the non-optimal economy. The SEEA formula for valuing depletion effectively partitions the total rent on extraction into a depletion component and a residual rent (cf. El Serafy 1989). Since only the depletion component has an impact on social welfare, by implication the residual rent is in fact income that can be consumed without affecting social welfare.

5 Conclusions

This analysis of non-optimal DHS economies suggests that the valuation of depletion in the SEEA (2012) is useful for assessing sustainability. The findings on the DHS economy show that the generalized Hartwick Rule for sustainability will apply under two assumptions—that marginal extraction costs are constant, and that extraction declines at a fixed rate.

The analysis in Sect. 2 frames the allocation rule for a simple non-optimal extractive economy. In addition to feasibility constraints, two basic (and interacting) rules determine the path of the economy—an extraction rule which determines the quantity of resource extracted at each point in time, and a saving rule which determines both how much wealth is created and how much consumption the economy will enjoy at each point. Within this framework the variant of the Hartwick Rule traditionally assumed in the resource accounting literature—set gross investment to equal to the change in the total value of the resource as a result of extraction—results in an economy with declining social welfare if this saving rule is followed over time.

Section 3 derives the correct policy rule for sustainability—set gross investment to be greater or equal to the value of resource depletion as measured in the SEEA. That is, depletion-

[11] Note that these capital gains are endogenously determined as a result of the depletion process. Vincent et al. (1997) and Hamilton and Bolt (2004) show that exogenous capital gains, resulting from trends in world prices, do contribute to social welfare in resource exporting countries.

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adjusted net saving should be greater or equal to 0.[12] The assumptions required to derive this result are not overly stringent: a constant rate of decline in extraction, and constant marginal extraction costs. Declining production from a fixed stock of resources is a fairly standard assumption for extractive activities, reflecting declining resource quality as the stock is depleted. Constant marginal extraction cost is at least a plausible description of the extractive process, and it is capable of refutation if extraction cost functions can be estimated. If there are increasing marginal costs of extraction then Sect. 3 shows that setting depletion-adjusted net saving greater or equal to 0 will produce increases in wellbeing—but this comes at the cost of the relationship between negative net saving and declines in wellbeing being dependent upon the difference between marginal and average extraction costs. If stock effects increase the extraction cost then the linkage between current growth in consumption and current genuine saving is dependent upon specific empirical factors.

Assuming that marginal extraction costs are constant, we show that the unit value of depletion p in the non-optimal DHS economy grows at a rate less than the rate of interest and that the value of depletion will be less than the total rents on extraction. It is worth recalling Dixit et al. (1980), who show that the Hartwick Rule, building on the Hotelling Rule, produces the maximal constant consumption path. For our analysis of the SEEA it is likely (but not definitively proven) that any constant level of consumption achieved by holding genuine saving equal to zero will not be the maximum constant level that could be achieved. This is because no maximization of the value of the resource deposit is assumed.

The policy application of these findings is quite direct, given the typical situation where exhaustible resources are owned by the government and exploited by private operators. Government should aim to capture a significant portion of the value of resource production using a resource rent tax[13]—SEEA accounting, as shown above, would enable government to estimate the depletion portion of total rents. This depletion portion of rents can then be invested, either through normal fiscal budgeting or through a sovereign wealth fund. Rules such as these can ensure that the public sector, at least, has positive genuine saving.

In terms of measurability, governments can (and do) use statistical surveys to collect data on quantities of resources extracted, as well as gross revenues and costs. Exploration and development licenses can yield data on proven and probable reserves. But governments do not always have sufficient information to estimate cost functions, which will limit the precision of estimated values of depletion, as explored in Sect. 3. But even imperfect estimates of genuine saving should be cause for concern when they are very low or negative.

The SEEA approach to accounting for exhaustible resources can clearly be extended to living natural resources that are subject to depletion as a result of unsustainable policies. One important example could be natural areas that provide flows of ecosystem services to the wider economy. Clearance and conversion of these natural areas is a process of depleting the stocks that provide ecosystem services. An accounting similar to that presented here can be applied to the problem of valuing this depletion.

Overall, these results provide welcome reassurance that practical wealth accounting in a world with multiple imperfections can say something quantitative about whether current policies, pursued into the future, will lead to rising social welfare and sustainability. SEEA (2012) is an important step forward.

[12] For brevity, in this paragraph we suppress the proviso that depletion-adjusted net saving should also be growing at a rate less than the interest rate.

[13] In practice, a variety of royalty and corporate taxes are typically used to capture rents, complicated by the information asymmetry between producers and governments.

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