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Sustainability and Hamiltonian Value

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Summary

The relationships among the Hamiltonian, NNP, and the level of sustainable consumption/utility have been widely misunderstood. This paper dispels the misconceptions and provides further new insight into these relationships. We show generally that for autonomous dynamic optimizing economies, a necessary and sufficient condition for sustainability is the *stationarity* of the current-value Hamiltonian. For autonomous cases, this stationarity condition generalizes Dixit *et a*l.'s (1980) "zero-net-aggregate-investment" rule of sustainability, which in turn generalizes Solow-Hartwick's sustainability rule. For non-autonomous cases, however, except when the net "pure time effect" is constant over time, the stationarity condition is unfulfilled. In non-autonomous cases, Weitzman's (1976) "stationary equivalence" result does *not* hold, and the current-value Hamiltonian will underestimate (overestimate) the true welfare level when the net "pure time effect" is positive (negative). However, for the special non-autonomous case of a time-dependent utility discount rate we obtain a condition on the discount rate function that upholds the results obtained for autonomous cases. In turn, this condition extends Michel's (1982) transversality condition for the infinite-horizon autonomous control problems to problems with time dependent discount rates.

Keywords: Sustainability, current-value Hamiltonian, net national product

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Sustainability and Hamiltonian Value

1. Introduction

Over the past quarter of a century, the unprecedented concern about the long-run consequences of environmental and natural resource use has confronted economists with two important intertwined questions. First, how should the conventional measure of national income be modified to properly take account of depletion of natural resources and the consequent environmental quality degradation? Second, how do the concepts of economic welfare and intergenerational equity relate to the modified national income measure? In response to these concerns, a vast (and still growing) literature has emerged, providing considerable valuable insights towards both questions.[1] Concerning the first question (green national accounting issue), the studies by Dasgupta and Heal (1979), Dasgupta (1990), Hartwick (1990), Mäler (1991), Dasgupta and Mäler (1991), Brekke (1994), Sefton and Weale (1996), and Heal and Kriström (1998) have been among the pioneering works. Regarding the second question (economic welfare and sustainability issue), original works of Solow (1974)(1986), Hartwick (1977), and Dasgupta and Mäler (1990), have been either further developed or extended in several important directions in papers by Asheim (1994), Aronsson and Löfgren (1995), Chichilnisky (1996), and Heal (1998), among others.

A starting point of most of these and related contributions has inherently been Weitzman's (1976) seminal paper. In that paper, Weitzman showed that under the specific assumptions of his model, at any time, the optimal current-value Hamiltonian equals the economy's net national product (NNP). Further, and perhaps more importantly, he provided the fundamental insight that, at any point in time, the optimal current-value Hamiltonian of a dynamically optimizing economy presents a (hypothetical) permanently constant consumption flow equivalent to the discounted value of the economy's optimal consumption path. This insight is sometimes referred to as "stationary equivalence" or Weitzman's basic result. On the other hand, Solow (1974) and Hartwick (1977) were the first to derive a condition for sustainability of a maximum constant consumption flow in the context of a closed economy using an exhaustible resource input and a reproducible capital with a constant technology to produce a consumption good. Their derived condition, known as Solow-Hartwick's sustainability rule, required that resource rents be reinvested in reproducible capital.

Unfortunately, however, the concurrence of Weitzman's "stationary equivalence" result with Solow-Hartwick's sustainability rule seems to have resulted in a widespread

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[1] For an overview of the theory of green national accounting, see the special issue of *Environment and Development Economics* (2000).

misinterpretation of Weitzman's result and thereby misinterpretations and confusion about the relationships among the current-value Hamiltonian, NNP, and sustainability condition. Yet, a correct understanding of these relationships is crucial to the development of a sound theoretical basis and methods for green national accounting. Building on many valuable insights from the previous literature, the present paper aims to (i) dispel the existing and potential misconceptions, (ii) generalize some of the basic results in the literature, (iii) provide further new insights into the relationships and, (iv) as a by product, extend an important transversality result in the optimal control theory due to Michel (1982). To this end, Section 2 briefly reviews the characteristics of the optimal consumption policy for the special case of a purely exhaustible resource economy. This special case greatly helps to bring out, in the clearest and simplest fashion, the prevailing misconceptions and consequent paradoxical results. Section 3 shows that, contrary to the usual *mis*interpretation of Weitzman's result (see, e.g., Mäler (1991, p.5)), the current-value Hamiltonian does *not* represent the maximum sustainable constant utility (consumption) flow. More importantly, it shows that a necessary and sufficient condition for sustainability in this sense is that the current-value Hamiltonian must be *stationary*. Section 4 shows that the stationarity condition holds generally for the class of dynamically optimizing economies characterized by an infinite-horizon, time-autonomous optimal control problem, of which the economy studied by Weitzman is a special case. As such, the stationarity condition generalizes Dixit *et al.*'s (1980) "zero-net-aggregate-investment" rule, which in turn is a generalization of Solow-Hartwick's "resource-rent-investment" rule of sustainability.

Section 5 considers the sustainability condition for the more general case of non-autonomous problems that arise from exogenous changes in the economy over time. We show that for such cases Weitzman's "stationary equivalence" result no longer holds, and that the current-value Hamiltonian *deviates* from the true welfare level by an amount equal to the discounted value of the flow of net "pure time effect." Furthermore, in non-autonomous cases, the stationarity of the current-value Hamiltonian no longer implies a constant utility (consumption) level unless the net pure time effect also remains constant over time. Section 6 addresses the sustainability condition for a special case of non-autonomous problems; namely, when the utility discount rate is time dependent. We obtain a new result, showing the specific condition for the discount rate function that ensures Weitzman's "stationary equivalence" result, Dixit *et al.*'s rule, and hence Solow-Hartwick's rule, all carry over from autonomous problems to such non-autonomous cases. In turn, this new condition extends Michel's (1982) result that in infinite horizon optimal control problems the maximum of the Hamiltonian converges to zero when time goes to infinity. Section 7 concludes.

2. The Exhaustible Resource Economy Revisited

Consider a purely exhaustible resource economy and, following Hotelling (1931), assume that: (i) it has a fully known and fixed initial stock of the resource of size $S_0 > 0$, (ii) the resource can be extracted costlessly, (iii) no technological change, (iv) population size remains constant, and (v) citizens' preferences are identical and presented by the representative consumer's utility function, $u(c)$, which is a twice differentiable, increasing, and strictly concave function of the resource consumption rate (*i.e.*, $u'(c) > 0$, $u''(c) < 0$ for all $c \geq 0$ $c \geq 0$), with $\lim_{c\to 0} u'(c) = +\infty$ and $\lim_{c\to\infty} u'(c) = 0$. The utilitarian social planner uses a social welfare function defined as the discounted sum of the representative consumer's utility flow and her objective is to plan a path of resource extraction and consumption that maximizes this social welfare function given the resource stock constraint. Formally, she plans to

$$\max_{c(t)} \int_0^\infty e^{-\rho t} u(c(t))\, dt \tag{1a}$$

$$s.t. \quad \dot{S}(t) = -c(t) \geq 0, \quad S(t) \geq 0, \quad S_0 \ (given) \tag{1b}$$

where $\rho > 0$ is the social time preference rate, assumed constant. Assuming the constraint $S(t) \geq 0$ holds, the current-value Hamiltonian of this problem is

$$H(c(t), S(t), \lambda(t)) = u(c(t)) - \lambda(t)c(t) \tag{2}$$

where $\lambda(t)$ is the utility shadow price of the resource stock. The first-order conditions for an interior optimal path are

$$\frac{\partial H}{\partial c} = u'(c(t)) - \lambda(t) = 0 \tag{3}$$

$$-\frac{\partial H}{\partial S} = 0 = \dot{\lambda}(t) - \rho\lambda(t) \tag{4}$$

and the transversality condition

$$\lim_{t\to\infty} e^{-\rho t}\lambda(t)S(t) = 0 \tag{5}$$

Differentiating (3) with respect to time, using (4), and denoting the elasticity of marginal utility of consumption by $\eta(c) = -\frac{c\,u''(c)}{u'(c)}$, the optimal consumption path is characterized by the familiar condition

$$\frac{\dot{c}(t)}{c(t)} = -\frac{\rho}{\eta(c)} \qquad (6)$$

It is immediate from (6) that, in general, the optimal policy for an exhaustible resource economy does *not* sustain a positive constant flow of consumption and hence utility. In fact, for the class of isoelastic utility function, $u(c) = \frac{c^{1-\eta}}{1-\eta}$, $0 < \eta < \infty$, along the optimal path, the consumption level declines exponentially over time at the constant rate of $\frac{\rho}{\eta}$. That is,

$$c(t) = c(0)\, e^{-\frac{\rho}{\eta} t} \qquad (7)$$

where from the resource stock constraint $\int_0^\infty c(t)dt = S_0$ and (7) one obtains $c(0) = \frac{\rho}{\eta} S_0$, so that (7) can be rewritten as

$$c(t) = \frac{\rho}{\eta} S_0\, e^{-\frac{\rho}{\eta} t}, \forall t \in [0, \infty) \qquad (8)$$

It is important to note that for an optimal policy to exist it is necessary that $\rho > 0$. In particular, in the limiting cases of no utility discounting, $\rho = 0$, or a pure egalitarian social welfare function where $\eta \to \infty$, a positive constant consumption path ($c(t) = \bar{c} > 0, \forall t \geq 0$), as implied by (6) for a general utility function, $u(c)$, cannot be sustained permanently by an exhaustible resource economy. On the other hand, the constant zero consumption path ($c(t) = 0, \forall t \geq 0$) implied by (8) for these limiting cases and when the utility function is isoelastic is evidently not optimal.

3. Sustainability and Current-Value Hamiltonian

In his classic paper, Weitzman (1976) investigated the welfare significance of NNP for a dynamic competitive economy that produced a single composite consumption good by utilizing services of capital, defined broadly to include a set of stocks of exhaustible natural resources and various kinds of reproductive capital stocks. A basic insight from that paper is that in a dynamically optimizing economy, along the optimal path, the current-value Hamiltonian *at time t*,

$H^*(t)$, is related to the optimal utilitarian welfare/consumption *path*, $u(c^*(\tau)), \tau \in (t, \infty)$, according to the following relationship[2]

$$\int_t^\infty e^{-\rho(\tau-t)} H^*(t)\, d\tau = \frac{H^*(t)}{\rho} = \int_t^\infty e^{-\rho(\tau-t)} u(c^*(\tau))\, d\tau \qquad (9)$$

Unfortunately, this relationship is often misunderstood by thinking that $H^*(t)$ measures the maximum *sustainable* level of utility (consumption). This misunderstanding becomes evident from a seeming paradox of the exhaustible resource economy analyzed in the previous section. For that economy, using (8), (4) and (3) in (2), it is easy to calculate that $H^*(t) = \frac{\eta}{1-\eta} (\frac{\rho S_0}{\eta})^{1-\eta} e^{-\rho (\frac{1}{\eta} - 1) t} > 0$ for $\eta < 1$. But, as was noted in the previous section, there is *no* sustainable positive consumption, and hence utility, level.

The explanation for this paradox lies in a correct understanding of what $H^*(t)$ precisely measures: in utility units, $H^*(t)$ is the "*stationary equivalent*" of the optimal welfare path.[3] In other words, it is the hypothetical maximum *constant* utility/consumption path whose *time-t discounted value* is equivalent to that of the (generally non-constant) optimal path, $u(c^*(\tau)), \tau \in (t, \infty)$. But, "stationary equivalence" does not mean "sustainability". That is, it does *not* imply, as it is often misunderstood, that our economy can actually enjoy a constant utility/consumption equal to $H^*(t)$ forever.

For the latter to be the case, $H^*(t)$ must satisfy an additional condition: it must be time invariant (or *stationary*). Otherwise, it does *not* represent an actually *sustainable* constant consumption level.[4] The important point to note is that even for autonomous optimal control problems, which characterize most of economic problems studied in the literature, the optimal current-value Hamiltonian need *not* be constant over time. In fact, for the economy analyzed in Weitzman (1976), which presents an example of such problems, we can prove the following

[2] Since *u(c)* is a single-valued, monotonic function of *c*, sustainability can be equivalently defined in terms of a constant utility or consumption flow. In fact, Weitzman assumed a linear utility function of the form *u(c(t))=c(t)*.

[3] Note that the utility units of $H^*(t)$ can be readily converted into real consumption units by choosing a dated utility numeraire such as $u^*(c(0))$ or generally $u^*(c(t))$ for any $t \geq 0$.

[4] The stationarity condition is also necessary and sufficient for time consistency of the optimal solution path; *i.e.*, for the optimal policy to be a sub-game perfect Nash equilibrium of the intergenerational allocation game where each generation has to decide how much to consume and how much capital stock to

proposition, which to our knowledge has not been shown in the previous literature, at least not explicitly

<u>Proposition 1</u>: *For Weitzman's economy, the stationarity of the optimal current-value Hamiltonian is a necessary and sufficient condition for permanently sustaining a constant utility/consumption path.*

<u>Proof</u>: Differentiating the second equation in (9) w.r.t. *t*, and using (9) again, one has

$$\dot{H}^*(t) = \rho[\rho\int_t^\infty e^{-\rho(\tau-t)} u(c(\tau))d\tau - u(c(t))] = \rho\,[H^*(t) - u(c(t))]$$

Sufficient condition: recalling that $u'(c) > 0, \forall c \geq 0$, it immediately follows that

$$\dot{H}^*(t) = 0, \forall t \geq 0 \quad \Rightarrow \quad H^*(t) = H^*(cons.) = u(c(t)), \forall t \geq 0 \quad \Rightarrow \quad c(t) = u^{-1}(H^*) = cons., \forall t \geq 0$$

Necessary condition: letting $c(\tau) = \overline{c} \geq 0, \forall \tau \geq 0$, so that $u(c(\tau)) = u(\overline{c}) \geq 0, \forall \tau \geq 0$, and performing the integral yields $\dot{H}^*(t) = 0, \forall t \geq 0$. ■

In the special case of our exhaustible resource economy, it is easy to verify that $\dot{H}^*(t) = -\rho\,(\frac{\rho S_0}{\eta})^{1-\eta}\, e^{-\rho\,(\frac{1}{\eta}-1)\,t} < 0, \forall t \geq 0$. That is, the stationarity condition is not satisfied, thus confirming that there is no sustainable consumption (utility) path for that economy.

4. Sustainability Condition: Generalization

It is quite tempting to go beyond Proposition 1 to explore if the *stationarity* of $H^*(t)$ is a general sustainability condition for any dynamically optimizing economy characterized by an infinite-horizon optimal control problem in which the instantaneous value function may take the most general form of $u(\mathbf{c}(t), \mathbf{s}(t), t)$, where $\mathbf{c}(t)$ is the vector of *n* control variables $c_i(t), i = 1, 2, ..., n$, $\mathbf{s}(t)$ is the vector of *m* state variables, $s_j(t),\ j = 1, 2, ..., m$ and the differential equations constraints take the general form of $\dot{s}_j = g_j(\mathbf{c}(t), \mathbf{s}(t), t), \quad j = 1, 2, ..., m$. Obviously,

leave for the future generations so that neither the present nor any of future generations will have an incentive to deviate from it.

a dynamic economy so characterized is general enough to present almost any interesting case that one may come across in the literature. For example, it includes cases where the utility derives not only from consumption of goods but also from capital stocks (for instance, the amenity values of environmental and natural resource stocks). It also includes cases where there is population growth or technological change over time.

Formally, let us consider the general optimal control problem [5]

$$\underset{\mathbf{c}(t)}{Maximize} \quad V = \int_0^\infty e^{-\rho t} u(\mathbf{c}(t), \mathbf{s}(t), t) dt$$

$$\begin{aligned} s.t. \qquad & \dot{s}_j = g_j(\mathbf{c}(t), \mathbf{s}(t), t), \qquad & j = 1, 2, ..., m, \\ & s_j(0) = s_{j0} \ (given) \qquad & j = 1, 2, ..., m. \end{aligned} \tag{10}$$

Let $\mathbf{c}^*(t), \mathbf{s}^*(t), \boldsymbol{\lambda}^*(t)$ be the solution to this problem, where $\boldsymbol{\lambda}^*(t)$ is the vector of costate variables. Then the current-value Hamiltonian $H(\mathbf{c}, \mathbf{s}, \boldsymbol{\lambda}, t) = u(\mathbf{c}, \mathbf{s}, t) + \sum_{j=1}^{m} \lambda_j(t) g_j(\mathbf{c}, \mathbf{s}, t)$ is maximized along the optimal paths. In general, the total time derivative of the current-value Hamiltonian is (for notational convenience, superscript *, denoting the optimal paths, is suppressed)

$$\frac{dH}{dt} = \frac{\partial H}{\partial t} + \sum_{i=1}^{n} \frac{\partial H}{\partial c_i} \dot{c}_i + \sum_{j=1}^{m} \frac{\partial H}{\partial s_j} \dot{s}_j + \sum_{j=1}^{m} \frac{\partial H}{\partial \lambda_j} \dot{\lambda}_j \tag{11}$$

Recalling that along the optimal path

$$\frac{\partial H}{\partial c_i} \dot{c}_i = 0, \forall i = 1, 2, ..., n \tag{12a}$$

(as either $\frac{\partial H}{\partial c_i} = 0$ for an interior solution or $\dot{c}_i = 0$ for a boundary solution),

$$-\frac{\partial H}{\partial s_j} = \dot{\lambda}_j - \rho \lambda_j, \forall j = 1, 2, ..., m, \tag{12b}$$

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[5] Without loss of generality we could also have a set of, say *r*, inequality constraints of the form $g_k(\mathbf{c}(t), \mathbf{s}(t), t)) \geq 0$, $k = 1, 2, ..., r$, and *h* equality constraints of the form $g_l(\mathbf{c}(t), \mathbf{s}(t), t) = 0$, $l = 1, 2, ..., h$ on control variables, where these constraints would be assumed to satisfy the rank condition of the constraint qualifications; namely that the matrix (of order *p.n*) of partial derivatives of the *p(>h)* binding constraints with respect to control variables be of rank *p*. For analytical convenience and to focus on the question at hand, we ignore these additional constraints and assume that the optimal control problems we are examining are all concave problems. In particular, we assume that the functions $\mathbf{c}(t)$, u and g_j satisfy all the continuity and differentiability conditions for the existence and uniqueness of solution to problem (10).

$$\dot{s}_j = \frac{\partial H}{\partial \lambda_j}, \forall j = 1, 2, ..., m \tag{12c}$$

and substituting from (12a)-(12c) in (11), we have

$$\frac{dH}{dt} = \frac{\partial H}{\partial t} + \rho \sum_{j=1}^{m} \lambda_j \dot{s}_j \tag{13}$$

Along an optimal path, equation (13) holds generally for *both* non-autonomous and autonomous cases, Weitzman's economy being a special case of the latter. It enables us to state the following proposition, which has not appeared in the previous literature

<u>Proposition 2</u>: *For any dynamic economy characterized by an <u>autonomous</u> infinite-horizon control problem, the stationarity of the current–value Hamiltonian is a necessary and sufficient condition for sustainability of a constant <u>utility</u> path.*

<u>*Proof*</u>*:* It suffices to show that Weitzman's fundamental relationship (9) holds true for any autonomous infinite-horizon control problem, so that the proof of Proposition 1 can be invoked. For an autonomous problem, the functions u or g_j s take the form of $u(\mathbf{c}(t), \mathbf{s}(t))$ and

$\dot{s}_j = g_j(\mathbf{c}(t), \mathbf{s}(t))$, so the current-value Hamiltonian is

$H(\mathbf{c}(t), \mathbf{s}(t), \boldsymbol{\lambda}(t)) = u(\mathbf{c}(t), \mathbf{s}(t)) + \sum_{j=1}^{m} \lambda_j(t) g_j(\mathbf{c}(t), \mathbf{s}(t))$. Since for such cases $\frac{\partial H}{\partial t} = 0, \forall t \geq 0$,

(11) reduces to

$$\frac{dH}{dt} = \rho \sum_{j=1}^{m} \lambda_j \dot{s}_j \tag{13a}$$

Recalling that $\dot{s}_j = g_j$, substituting (13a) in the expression for the optimal current-value Hamiltonian and rearranging terms yields the differential equation

$$\frac{dH(t)}{dt} = \rho \, [H(t) - u(\mathbf{c}(t), \mathbf{s}(t))] \tag{14}$$

which can be solved to give

$$\int_{t=\tau}^{\infty} e^{-\rho(t-\tau)} H(\tau) \, dt = \frac{H(\tau)}{\rho} = \int_{t=\tau}^{\infty} e^{-\rho(t-\tau)} u(\mathbf{c}(t), \mathbf{s}(t)) \, dt \tag{15}$$

for any $\tau \geq 0$ *along the optimal path.*[6] ■

<u>*Remark 1*</u>: It should be noted that in the general case of Proposition 2 where $u(\mathbf{c}(t), \mathbf{s}(t))$ is a vector-valued function of the flows of various consumption goods, sustainability is defined only in terms of a permanently constant *utility* path, and not of constant consumption paths. Accordingly, in invoking the proof of Proposition1 only the constancy of utility flow is relevant.

<u>*Remark 2*</u>: Recalling that $\sum_{j=1}^{m} \lambda_j \dot{s}_j$ is the value of *net aggregate investment* along the optimal path at any time, it is interesting to note from (13a) that for any $\rho > 0$

$$\frac{dH}{dt} = 0, \forall t \geq 0 \quad \Leftrightarrow \quad \sum_{j=1}^{m} \lambda_j \dot{s}_j = 0, \forall t \geq 0 \tag{13b}$$

That is, our stationarity condition ($\frac{dH}{dt} = 0, \forall t \geq 0$) for sustainability of autonomous dynamic economies generalizes the familiar "zero-net-aggregate-investment" rule which was originally derived by Dixit, Hammond, and Hoel (1980) only as a *sufficient* condition for sustainability[7] (see also Solow (1986), Hartwick (1977) and Mäler (1991) among others). In turn, the latter rule generalized Solow-Hartwick's sustainability rule of investing resources rents in a reproducible capital.[8] It is important to note that our stationarity condition is *both* a necessary and sufficient condition for sustaining a constant optimal utility path.[9]

<u>*Remark 3*</u>*:* Interpreting the value of the integral $W_t \equiv \int_t^{\infty} e^{-\rho(\tau - t)} u(c^*(\tau))\, d\tau$ in (9), or its generalized version $W_t \equiv \int_{t=\tau}^{\infty} e^{-\rho(t-\tau)} u(\mathbf{c}(t), \mathbf{s}(t))\, dt$ for the class of time-autonomous economies in (15), as economy's stock of "total wealth" (measured in utility units) at any time *t*, we arrive at

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6 Note that it is a necessary condition that along the optimal path $H(t)$ is bounded above so that $\lim_{t \to \infty} e^{-\rho t} H(t) = 0$, see Michel (1982).

7 Dixit, Hammond, and Hoel (1980) derived their *sufficiency* condition in a less general framework than that analyzed here, although they did not assume a constant discount rate. In section 6, we obtain the general sustainability condition when the discount rate is time dependent.

8 Obviously, in an economy with heterogeneous capital stocks if net aggregate investment is always positive, net national product and hence the optimal utility level can rise over time.

9 By a very different approach, Withagen and Asheim (1998) show that the converse of Solow-Hartwick's rule (the necessary condition) holds in general for an economy with stationary preferences and technology.

another basic and familiar insight from Weitzman's fundamental relationship (reflected by the second equality in (9), or from its generalized form here for autonomous economies (reflected by the second equality in (15). That is, along the optimal path, at any time the current-value Hamiltonian is the imputed "interest" on the economy's stock of wealth (Solow (1986), Hartwick (1994) and others). Now, according to Proposition 2 for autonomous economies, *only under the condition of stationarity of the current-value Hamiltonian* ($\frac{dH}{dt} = 0, \forall t \geq 0$), the utility level along the optimal path remains permanently constant ($u(\mathbf{c}(t), \mathbf{s}(t) = \bar{u}, \forall t \geq 0$), implying in turn that the value of wealth remains intact ($W_t = \frac{\bar{u}}{\rho} \equiv \bar{W}, \forall t \geq 0$). In that case, the optimal current-value Hamiltonian may be interpreted as *Hicksian* income, in utility terms; that is, the maximum constant utility level (equal to interest on wealth, $H = \rho \bar{W} = \bar{u}$) that can be permanently sustained. It is important to reemphasize here that while for all autonomous economies the current-value Hamiltonian can be interpreted as interest on total wealth, it represents the *sustainable* constant utility (consumption) level *if, and only if*, it is time stationary. Unfortunately, the neglect of the latter condition in the literature has led to the common mistake of interpreting the current-value Hamiltonian as the sustainable constant utility (consumption) level (see, for example, Mäler (1991) and Hartwick (1994)(2000, Ch.3, P.53)). While under the specific assumptions of Weitzman's model, the optimal current–value Hamiltonian at any time equals NNP, it does *not*, contrary to the prevailing mistaken belief, equal Hicksian income unless the current-value Hamiltonian is stationary.

Remark 4: In the special case of a purely exhaustible resource economy, since by definition there is no accumulable capital stock and since no optimal policy exists for $\rho = 0$, it follows from (13a) that

$$\frac{dH}{dt} = \rho\, \lambda(t)\, \dot{S}(t) = -\rho\, \lambda(t)\, c(t) < 0 \tag{13c}$$

i.e., the stationarity condition for sustainability is never met and hence there exists no sustainable (positive) constant utility (consumption) level. This reconfirms and generalizes the result in the previous section for the isoelastic utility function. Note that, in fact, for such an economy, along the optimal path the level of well being *declines* over time.

5. Sustainability Condition: Non-autonomous Cases

We now return to problem (10) and invoke equation (13) to examine the sustainability condition for the more general case of time *non-autonomous* economies where at least one of the functions $u(\mathbf{c}(t),\mathbf{s}(t),t)$ or $g_j(\mathbf{c}(t),\mathbf{s}(t),t)$ depends explicitly on *t*. Examples of situations giving rise to non-autonomous cases include exogenous changes over time in population size, in taste and preferences, in the state of technology, in the rate of physical stock depreciation or growth (for instance, the decay of the CO_2 stock in the atmosphere or growth of forest stocks with time, or additions to reserves of mineral deposits due to exogenous new discoveries).

As in problem (10), we continue to assume a constant discount rate $\rho > 0$. Thus, along an optimal path, one has

$$\frac{\partial H}{\partial t} = \frac{\partial u}{\partial t} + \sum_{j=1}^{m} \lambda_j(t) \frac{\partial g_j}{\partial t} \tag{16}$$

which measures the *net* change in the optimal current-value Hamiltonian at time *t* due purely to passage of time alone. We may term this as net *"pure time effect"*, which may be positive (for example in the case of exogenous technological progress alone) or negative (for example when there is exogenous population growth or when the rate of stock depreciation changes with time).

Recalling that $\dot{s}_j = g_j$ and substituting for $\sum_{j=1}^{m} \lambda_j \dot{s}_j$ from the Hamiltonian expression into (13), one has along the optimal path

$$\frac{dH}{dt} = \frac{\partial H}{\partial t} + \rho [H(t) - u(t)] \tag{17}$$

Solving the differential equation (17) yields, for any $\tau \geq 0$

$$\rho \int_{\tau}^{\infty} e^{-\rho(t-\tau)} H(\tau)\, dt = H(\tau) = \rho \int_{\tau}^{\infty} e^{-\rho(t-\tau)} u(t)\, dt - \int_{\tau}^{\infty} e^{-\rho(t-\tau)} \frac{\partial H(t)}{\partial t} dt \tag{18}$$

where $\frac{\partial H}{\partial t}$ is given by (16).

Relationship (18) is a general result, leading to further important insights.[10]

[10] To be sure, several interesting special cases of this general result have been studied in the literature. For instance, Weitzman (1997), Weitzman and Löfgren (1997), and Hartwick and Long (1999) have studied the conditions of a constant consumption path when technology, output prices, or interest rates change exogenously over time. Also, in an insightful paper, Aronsson and Löfgren (1995) show how the optimal Hamiltonian value as a welfare measure is modified in the presence of an exogenous technological change, stock pollution externality, or stochastic production factors. The result furnished in (18) is, however, a more general and explicit one, embracing these and many other possible specific cases where the pure time effects are present.

First, since $\frac{\partial H}{\partial t} = \frac{\partial u}{\partial t} + \sum_{j=1}^{m} \lambda_j(t) \frac{\partial g_j}{\partial t}$ is not identically equal to zero *for all* $t \geq 0$, the second integral on the RHS of (18) does not vanish *for all* $\tau \geq 0$, so that, on comparing (18) with (15) or with (9), we have

<u>Proposition 3</u>: The "stationary equivalence" property of the current value Hamiltonian (Weitzman's fundamental relationship) can be generalized only for time-autonomous dynamic economies but does <u>not</u> hold for non-autonomous cases.

It then immediately follows from (18)

<u>Corollary 1</u>: The interpretation of the optimal current-value Hamiltonian as interest (return) on economy's wealth (see Remark 3 above), and hence as NNP, does <u>not</u> hold for time non-autonomous economies. For these cases, at any time t, the current-value Hamiltonian will under (over) estimate the true welfare level by an amount equal to the discounted value of the net "pure time effect" ($\int_{\tau}^{\infty} e^{-\rho(t-\tau)} \frac{\partial H(t)}{\partial t} dt$ *) if this effect is positive (negative).*

Second, by (17), one has

$$\frac{dH}{dt} = 0, \forall t \geq 0 \quad \Rightarrow u(\mathbf{c}(t), \mathbf{s}(t), t) = \bar{H} + \frac{1}{\rho}\frac{\partial H}{\partial t}, \forall t \geq 0 \qquad (18a)$$

So that,

<u>Corollary 2</u>: In contrast to the case of time-autonomous economies, for non-autonomous cases the stationarity of the current-value Hamiltonian is not a sufficient condition for sustainability of a constant utility (consumption) level unless in the exceptional case where the net "pure time effect", $\frac{\partial H}{\partial t}$*, also remains constant (including 0) over time.*

Third, it also follows from (13) that

<u>Corollary 3</u>: For time non-autonomous economies, Dixit et al.'s "zero-net-aggregate-investment" rule, and a fortiori Solow-Hardwick's "resource-rent-investment" rule, is not a sufficient condition for sustaining a constant utility (consumption) path.

Notice that for the non-autonomous case, the stationarity of the current-value Hamiltonian implies that Dixit *et al.*'s "zero-net-aggregate-investment rule" needs to be modified according to $\sum_{j=1}^{m} \lambda_j \dot{s}_j = -\frac{1}{\rho}\frac{\partial H}{\partial t} = -\int_{t}^{\infty} e^{-\rho(\tau-t)} \frac{\partial H(t)}{\partial t} d\tau$. Accordingly, at any time, the net aggregate investment can be *negative* (positive) as long as the disinvestment (investment) in aggregate capital stocks is exactly made up for by a constant positive (negative) flow of "pure time effect" of equivalent (discounted) value. Roughly speaking, this means that the economy can afford to let its national wealth run down (and hence raise its consumption level) provided it enjoys a free (windfall) flow of benefits (for example due to exogenous technological progress) of the same discounted value. Conversely, it should *optimally* make up for exogenous losses (for example due to transboundary environmental externalities or an exogenous deterioration in its terms of trade) by building up the aggregate capital stock.

6. Sustainability Condition: Time-dependent Discount Rate

A special non-autonomous case is when the instantaneous discount rate $\rho(t)$ varies with time, so that, denoting by $\psi(t) \equiv \int_0^t \rho(s)\,ds$ the discount rate over the interval of time (0,t], the discount factor at any time *t* is $e^{-\psi(t)}$. As is familiar, in this case the current-value Hamiltonian expression remains as before but equations (12b) and (13) are modified as

$$-\frac{\partial H}{\partial s_j} = \dot{\lambda}_j - \rho(t)\,\lambda_j\,,\ \forall j = 1,2,...,m \qquad (19)$$

and

$$\frac{dH}{dt} = \frac{\partial H}{\partial t} + \rho(t)\sum_{j=1}^{m} \lambda_j\ \dot{s}_j \qquad (20)$$

Concentrating on cases where, as in the general autonomous problem, none of the functions u or g_j s depends explicitly on *t*, so that $\frac{\partial H}{\partial t} \equiv 0$, (20) simplifies to

$$\frac{dH}{dt} = \rho(t)\sum_{j=1}^{m} \lambda_j\ \dot{s}_j \qquad (20a)$$

which is the analog of (13a) for the case of constant discount rate. Following the same steps leading to (14), one obtains the modified version of (14) as

$$\frac{dH(t)}{dt} - \rho(t)\,H(t) = -\,\rho(t)\ u(\mathbf{c}(t),\mathbf{s}(t)) \qquad (21)$$

Solving this differential equation yields *for all* $\tau \geq 0$

$$H(\tau) = \int_{\tau}^{\infty} \rho(t)[e^{-(\psi(t)-\psi(\tau))}\,u(\mathbf{c}(t),\mathbf{s}(t))]\,dt + \lim_{t\to\infty}[e^{-(\psi(t)-\psi(\tau))}H(t)] \qquad (22)$$

Condition (22) establishes a new result in the literature and is important in two respects. Second, from a purely technical viewpoint, with a time-dependent utility discount rate, one can no longer necessarily use the well-known result of Michel (1982), showing that the present value Hamiltonian corresponding to a well defined optimal control problem approaches zero when time goes to infinity. Instead, the result must be defined conditional on the assumption, which in the context of the present paper is equivalent to assuming that the sum of utility discount rates approaches infinity when time goes to infinity.

Two noteworthy points emerge from (20a), (21), and (22). First, it is noted from (22) that the assumption of bounded current-value Hamiltonian along the optimal path does not ensure that the second term on the RHS of (22) vanishes. For this to be the case, the instantaneous discount rate function $\rho(s)$ must satisfy the following condition

$$\lim_{t\to\infty} \psi(t) = \lim_{t\to\infty} \int_0^t \rho(s)\, ds = +\infty \tag{23}$$

Thus, from a purely technical viewpoint, with a time-dependent utility discount rate, one can no longer necessarily use the well-known result of Michel (1982), showing that the present value Hamiltonian corresponding to a well defined optimal control problem approaches zero when time goes to infinity. Instead, the result must be defined conditional on the assumption, which in the context of the present paper is equivalent to assuming that the sum of utility discount rates approaches infinity when time goes to infinity. Accordingly, condition (23) extends Michel's result for the case of time-dependent discount rate.

Second, the economic interpretation of condition (22) reveals that, if the utility discount rate is time dependent, then in general the current-value Hamiltonian along the optimal trajectory no longer represents the discounted value of the imputed interest income (in utility terms), but that *plus* the limit of the Hamiltonian value as time approaches infinity. Consequently, for the time-dependent discount rate Proposition 3 is modified as

<u>Corollary 4</u>: *When the discount rate varies with time, the "stationary equivalence" property of the current value Hamiltonian (i.e., Weitzman's fundamental result generalized as* $\int_\tau^\infty \rho(t)\, e^{-(\psi(t)-\psi(\tau))} H(\tau) dt = \int_\tau^\infty \rho(t) e^{-(\psi(t)-\psi(\tau))}\, u(\mathbf{c}(t), \mathbf{s}(t))\, dt$ *) holds if and only if the discount rate function satisfies the condition* $\lim_{t\to\infty} \int_0^t \rho(s)\, ds = +\infty$.

This is an important result for it modifies the claims in the literature (see, for example, Svensson (1986) and Asheim (1994, P. 261)) that Weitzman's fundamental result does not hold without the assumption of a constant utility discount rate. It shows that the result holds provided the discount rate function satisfies the condition $\lim_{t\to\infty} \int_0^t \rho(s)\,ds = +\infty$, which is obviously the case as long as the discount rate does not decline too fast with time. One example of such a discount rate function which has recently received considerable attention in the economic literature (see, e.g., Liabson (1996)(1997) among others) is the hyperbolic discount function. Presented generally in the form of $\rho(t) = \dfrac{k_1}{1+k_2\,t}$, $(0 < k_1 < 1,\ k_2 > 0)$, it is readily checked that $\lim_{t\to\infty} \int_0^t \rho(s)\,ds = \dfrac{k_1}{k_2} \lim_{t\to\infty} \ln(1+k_2\,t) = \infty$. Note that this condition is not satisfied, for example, by the exponentially declining function $\rho(t) = k_1 e^{-k_2\,t}$, for which $\lim_{t\to\infty} \psi(t) = \dfrac{k_1}{k_2}$. However, it should be noted that even if the utility discount rate function satisfies condition (23), the implied optimal sustainable consumption path will be time inconsistent (see, Strotz (1955-1956), unless the social planner can somehow precommit to it.

Further, it is noted that the integral $\int_\tau^\infty \rho(t) e^{-(\psi(t)-\psi(\tau))}\, u(\mathbf{c}(t), \mathbf{s}(t))\,dt$ can no longer be interpreted as the interest on stock of wealth in the same precise sense as in the case of constant discount rate $\rho(t) = \rho$ (see *Remark 3* above), for it now presents the discounted value of the stream of interests on the optimal utility path. Thus, by (22) and (23), we can state

<u>Corollary 5</u>: *When the discount rate varies with time, the optimal current-value Hamiltonian (or NNP) does <u>not</u> in general represent the interest on the economy's wealth. It presents the discounted value of the flow of interest on the optimal utility path <u>only if</u> the discount rate function satisfies the condition* $\lim_{t\to\infty} \int_0^t \rho(s)\,ds = +\infty$.

This corollary has an important implication for green national accounting: while it cautions us against equating the interest on wealth as green NNP when the discount rate (or the consumption rate of interest) varies with time (as noted by Svensson (1986, 155), Hung (1993, p.381), and Asheim (1994, p. 261)), it also shows the condition under which such a practice would be valid.

Second, it easily follows from (20a) and (21) that

$$\frac{dH}{dt} = 0,\ \forall t \geq 0 \Rightarrow \sum_{j=1}^{m} \lambda_j\ \dot{s}_j = 0, \forall t \geq 0,\ \Rightarrow H(t) = \bar{H}(cons.) = u(t), \forall t \geq 0$$

That is, as in the case of constant discount rate, the stationarity of the current-value Hamiltonian , and hence the "zero-net-aggregate-investment" rule is still sufficient for sustainability of a constant positive utility level (equal to the constant Hamiltonian value). However, contrary to the case of constant discount rate, the reverse is no longer generally true. This latter is seen by noting from (22) that for a constant utility flow, $u(t) \equiv \bar{u} > 0$, one has for all $\tau \geq 0$ (recalling that $\dot{\psi}(t) = \rho(t)$)

$$H(\tau) = \bar{u} + \lim_{t\to\infty} e^{-(\psi(t)-\psi(\tau))}(H(t) - \bar{u}) \tag{24}$$

So that unless $\bar{u} = \lim_{t\to\infty} H(t)$ or condition (23) is met, $H(\tau) \neq \bar{u}$ for all $\tau \geq 0$, *i.e.*, a constant utility level does not generally imply a constant current-value Hamiltonian (equal to the constant utility level). We can therefore state the following

<u>Proposition 4:</u> *Even when the discount rate varies with time, the stationarity of the current-value Hamiltonian, and hence Dixit et al.'s "zero-net-aggregate-investment" rule, (a fortiori Solow-Hardwick's "resource-rent-investment" rule) is still a sufficient condition for sustainability of a constant utility (consumption) path (equal to the optimal current-value Hamiltonian), but the converse is no longer true unless either* $\lim_{t\to\infty} \int_0^t \rho(s)\,ds = +\infty$ *or* $\lim_{t\to\infty} H(t) = \bar{u}$.

According to the first part of Proposition 4, it is incorrect to think that Dixit *et al.*'s rule, or Solow-Hardwick's rule, of sustainability is valid only if the utility discount rate is constant. The second part of the Proposition shows the specific condition under which the reverse of these rules also holds despite a variable discount rate. On both accounts, Proposition 4 weakens Svensson's (1986, p.154, p.155) claim of the contrary. As we have seen, in general, for any autonomous problem, the stationarity of the current-value Hamiltonian is a sufficient condition for sustainability regardless of whether the discount rate is constant or time-dependent. But, while for a constant discount rate, the stationarity is also a necessary condition, for a time-dependent discount rate, it is so provided as time goes to infinity, either the discount *factor* approaches zero or the optimal Hamiltonian approaches the constant utility level. Obviously, these results also extend to Dixit *et. al*'s and Solow-Hartwick's rules.

7. Conclusions

This paper has scrutinized the fundamental relationships among the concepts of current-value Hamiltonian, sustainability, and NNP. Building on a body of insightful pioneering works, it has clarified some of the misconceptions surrounding these relationships in the green accounting literature, generalized and extended some of the previous basic results obtained in that literature for special cases, and provided new insights into the relationships.

Specifically, we have argued that contrary to common interpretation, the current–value Hamiltonian does *not* represent the maximum sustainable level of consumption (utility). We have shown generally that for any dynamic optimizing economy presented by an autonomous optimal control problem, a necessary and sufficient condition for sustainability in that sense is that the current-value Hamiltonian should be *stationary* over time. Accordingly, even when the optimal current-value Hamiltonian equals NNP, it is only under the stationarity condition that it can be interpreted as Hicksian income. For the more general case of time non-autonomous economies, characterized by exogenous changes in the economy over time, we have shown that the "stationary equivalence" property of the current-value Hamiltonian does not carry over, with two important implications. First, the optimal current-value Hamiltonian can no longer be interpreted as interest on the economy's wealth, and hence as NNP. In fact, equating NNP with the current-value Hamiltonian will lead to an underestimation (overestimation) of the true level of well being if the net "pure time effect" is positive (negative). Second, the stationarity of the current-value Hamiltonian, and hence the "zero-net-aggregate-investment" rule, will no longer be a sufficient condition for permanently sustaining a constant utility (consumption) level. While these results pose conceptual and measurement difficulties for green national accounting, few economists may view continued exogenous changes, such as technological progress, population growth, preference shifts, or environmental externalities, as realistic possibilities. Interestingly, for one special, but important, non-autonomous case– namely, a time dependent discount rate- we have shown that the results obtained under the general autonomous case do prevail provided the discount rate function satisfies a certain mild condition, which is satisfied, for example, by a hyperbolic discount rate function.

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