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Sustainability and Technical Progress

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Abstract

A rigorous model connects together the following three basic concepts: (1) "sustainability" — meaning the generalized future power of an economy to consume over time; (2) "Green NNP" — meaning a current measure of national income that subtracts off from GNP not just depreciation of capital but also, more generally, depletion of environmental assets evaluated at current efficiency prices; (3) "technological progress" — meaning a projection onto the future of the so-called "Solow residual". A simple general formula is derived. Some crude calculations suggest a possibly strong effect of the residual, which hints that our best present estimates of long-term sustainability may be largely driven by predictions of future technological progress.

I. Introduction

"Sustainability" has become a popular catchword in recent years. The word itself is subject to various interpretations. In an oft-cited phrase, the Bruntland Commission[1] defined "sustainable development" to be "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." While it is not typically stated explicitly, the basic underlying concept behind most notions of sustainability in the literature would appear to be some implicit measure of the economy's generalized capacity to produce economic well-being over time.

In this paper "sustainability" is defined to be the annualized equivalent of the present discounted value of consumption that the economy is capable of achieving. More precisely, "sustainability" of an economy is the hypothetical constant or "annuity-equivalent" level of consumption that would yield the same present discounted value as the actual consumption trajectory the economy is able to deliver. In this context, "sustainable development" might refer to a time path whose "sustainability" over the future is never less than its current consumption.

Now it turns out that there is a rather remarkable theoretical relationship between "sustainability", defined above, and what might be called

[1] WCED (1987); p. 43.

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"Green NNP" — the net aggregate that subtracts off from GNP not just depreciation of capital but also the value of depleted natural resources evaluated at competitive market prices. Under certain conditions, Green NNP exactly equals sustainability.[2]

The force of this result is perhaps not sufficiently appreciated. A future "sustainability crisis" caused by the exhaustion of a critical resource looming over the horizon should manifest itself *now*. Sustainability, which is essentially a measure of *future* consumption, is, at least in principle, exactly reflected in *current* Green NNP.

While this result can serve as a powerful conceptual guide for indicating how to think about the relationship between sustainability and national income accounting, its practical applicability is somewhat limited by the assumptions of the model.

The most restrictive assumption, by far, is the absence of technological progress. The existing result that a theoretically correct measure of welfare just exactly equals a theoretically correct measure of Green NNP relies completely on the time-autonomy of the system. But, to the extent that whatever endogenous and exogenous factors thought to underlie technical change have been ignored, the situation can be interpreted "as if" there exists a time-dependent residual shift factor that increases productivity but does not show up anywhere in national income accounts, and hence is ignored by the existing framework.

The consequences of technical change being absent from the standard time-autonomous model might be quite serious for the basic welfare interpretation of Green NNP. We know that future growth is largely driven by the rate of technological progress, however it is conceptualized. Since Green NNP theoretically equals annuity-equivalent future consumption possibilities *without* the "Solow residual", the proper measure of annuity-equivalent future consumption possibilities *with* the "Solow residual" might conceivably call for a sizable upward adjustment of Green NNP.

This paper extends the existing standard framework to include technological progress. Mathematically, I expand the model of my 1976 paper to cover a situation where the technology depends on time. The results of the earlier paper can henceforth be viewed as a special case of the more general results obtained here.

An exact expression is derived that indicates the appropriate upward correction of Green NNP required by the existence of technological progress or any other form of time dependency. A rough calculation based on reasonable values of the relevant parameters suggests that the required corrections may be sizable — perhaps around 40 per cent or more of

[2]This is a rephrasing of the basic result in Weitzman (1976).

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conventionally-measured national product. A possible implication could be that long-term sustainability, like so much else about the future, is largely driven by projections of technological progress.

I should make clear at the outset that the treatment of time dependency *per se* is not original to this paper, since there already exists a sizable literature on the subject. Weitzman (1976) sketched the mathematical outlines of a corrective expression. Important formal contributions were made by Kemp and Long (1982), Löfgren (1992), Aronsson and Löfgren (1993), Asheim (1996), Nordhaus (1995), Hartwick (1995) and others. From this literature it emerges that there are several ways to express the effects of time dependency, each one having a somewhat different interpretation. The main contribution of the present paper is to derive a simple but quite general formula in which the Solow residual appears as a natural link connecting sustainability with national income accounting when there is technological progress. My hope is that this expression may be found useful because it is interpretable in terms of some already-familiar concepts from growth theory and other areas.

II. A Formulation of the Basic Problem

To make the problem analytically tractable, we abstract heroically in the spirit of Weitzman (1976).

First of all, for simplicity it is assumed that (in effect) there is just one composite consumption good. It might be calculated as an index number with given price weights, or as a multiple of some fixed basket of goods, or more generally as any cardinal utility function. The important thing is that the consumption level in period t can be unambiguously registered by the single number $C(t)$. Thus, the paper assumes away all of the problems that might be associated with constructing an "ideal measure" of consumption akin to a utility function. Purging consumption of the index number problem will allow us to focus more sharply on the general meaning and significance of combining it with investment when there is technological progress.

As in my earlier paper, the notion of "capital" used here is meant to be quite a bit more general than the traditional "produced means of production" like equipment and structures. Most immediately, pools of natural resources are considered to be capital. Human capital should also be included, if we knew how to measure it. Under a very broad interpretation, environmental assets generally might be treated as a form of capital.[3]

[3] Mäler (1991) includes a discussion of some of the relevant issues here.

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Suppose that altogether there are n capital goods, including stocks of natural resources. The stock of capital of type j ($1 \leq j \leq n$) in existence at time t is denoted by $K_j(t)$, and its corresponding net investment flow is

$$I_j(t) = \dot{K}_j(t) \equiv \frac{\mathrm{d}K_j(t)}{\mathrm{d}t}. \tag{1}$$

The n-vector $\mathbf{K} = \{K_j\}$ denotes all capital stocks, while $\mathbf{I} = \{I_j\}$ stands for the n-vector of net investments. Note that the net investment flow of a non-renewable natural capital like oil reserves would typically be negative.

The production-possibilities set at time t with capital stock $\mathbf{K}$ is denoted here by $S(\mathbf{K}; t)$. My previous paper, Weitzman (1976), treated only the special case of time-independence where, in effect, the production possibilities set was restricted to be a function of $\mathbf{K}$ alone. Thus, in my earlier paper $S = S(\mathbf{K})$, while the present paper treats the more general case $S = S(\mathbf{K}; t)$. Mathematically, this is the only substantive difference between the two papers.

The consumption-investment pair $(C, \mathbf{I})$ is producible at time t if and only if

$$(C, \mathbf{I}) \in S(\mathbf{K}(t); t). \tag{2}$$

Let P_j represent the price of investment good j relative to a consumption-good price of unity. Let $\mathbf{P}$ denote the n-vector of investment-good prices. A *Green-Net-National-Product Function* (expressed in real terms with consumption as numeraire) could be defined as follows:

$$G(\mathbf{K}, \mathbf{P}; t) \equiv \underset{(C, \mathbf{I}) \in S(\mathbf{K}; t)}{\text{maximum}} [C + \mathbf{PI}]. \tag{3}$$

A value of $Y(t) = G(\mathbf{K}(t), \mathbf{P}(t); t)$ might legitimately be called "inclusive" or "Green" NNP because the value of depleted natural resources, as well as capital depreciation, has been subtracted from GNP. While this paper could get by with much weaker assumptions, for convenience it will be assumed that the Green-NNP function $G(\cdot)$ is smooth in all its arguments.

A *feasible* trajectory $\{C(t), \mathbf{K}(t)\}$ is one satisfying for all $t \geq 0$ the conditions

$$(C(t), \dot{\mathbf{K}}(t)) \in S(\mathbf{K}(t); t) \tag{4}$$

and

$$\mathbf{K}(0) = \mathbf{K}_0. \tag{5}$$

where $\mathbf{K}_0$ is the original endowment of capital available at starting time $t = 0$.

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Generally speaking, there are an infinite number of feasible trajectories. We can narrow feasible trajectories down to a unique family by presuming a competitive-like economy with a fixed own rate of return on the consumption good equal to r. A *competitive* trajectory $\{C^*(t), \mathbf{K}^*(t)\}$ with *real interest rate* r is any feasible trajectory for which there exists an n-vector of investment prices $\{\mathbf{P}(t)\}$ such that, evaluated at all $t \geq 0$ along the trajectory

$$G(\mathbf{K}^*(t), \mathbf{P}(t), t) = C^*(t) + \mathbf{P}(t)\dot{\mathbf{K}}^*(t) \tag{6}$$

and, for each j,

$$\frac{\partial G}{\partial K_j} = rP_j(t) - \frac{\mathrm{d}P_j}{\mathrm{d}t}. \tag{7}$$

Equation (6) just states that what is actually produced by the economy at any time maximizes its income — in other words, relative prices are equal to marginal rates of transformation. Condition (7) is the well-known intertemporal efficiency condition of a competitive capital market.[4]

Actually, equations (6) and (7) are necessary Pontryagin-type conditions[5] for any solution to the optimal control problem of maximizing the expression

$$\int_0^\infty C(t)\, \mathrm{e}^{-rt}\, \mathrm{d}t \tag{8}$$

subject to the constraint

$$(C(t), \dot{\mathbf{K}}(t)) \in S(\mathbf{K}(t); t) \tag{9}$$

and obeying the initial condition

$$\mathbf{K}(0) = \mathbf{K}_0. \tag{10}$$

Thus, $\{C^*(t), \mathbf{K}^*(t)\}$ can be considered a solution of the optimal control problem (8)–(10), and what we have been calling "inclusive" or "Green" Net National Product — the expression (6) — is the current value Hamiltonian maximized over the control variables. Therefore, an alternative but equivalent approach to the one taken in this paper would be to ask what, if anything, the Hamiltonian along an optimal growth path measures when the production possibilities set exhibits time dependence.

In the optimal control context, r stands for the rate of pure time preference or, alternatively, a fixed probability that the world ends in any given period. By either interpretation, the discount factor $\{\mathrm{e}^{-rt}\}$ serves as a

[4] See Weitzman (1976, footnote 5).
[5] See Weitzman (1976, footnote 6).

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natural system of weights for aggregating or averaging variables over time. The next section makes extensive use of this philosophy and this mechanism.

III. Sustainability and Green NNP

Let $X(t)$ represent any time-dependent variable. The annuity-equivalent value of X, which henceforth will be denoted by $[X]$, is the hypothetical constant level of X that would yield the same present discounted value at time zero as the time series $\{X(t)\}$. The discount rate to be used here is "naturally" the same value of r that is inherent in the entire analytical framework.

By this definition, $[X]$ satisfies the equation

$$\int_0^\infty [X]\, e^{-rt}\, dt = \int_0^\infty X(t)\, e^{-rt}\, dt \tag{11}$$

which can be rewritten as

$$[X] \equiv r \int_0^\infty X(t)\, e^{-rt}\, dt. \tag{12}$$

It will be seen at once that $[X]$ is interpretable as a weighted time-average of $\{X(t)\}$, with weights $\{e^{-rt}\}$ applying at time t.

To be able to make any formal statements about "sustainability", the concept must first be defined formally. The basic motivating idea behind the concept of "sustainability" underlying most of the literature would appear to be some "good" aggregate measure of the economy's generalized power to sustain future consumption.

In this paper, sustainability is defined formally to be the hypothetical constant "annuity-equivalent" level of consumption that would yield the same present discounted value as the optimal consumption trajectory $\{C^*(t)\}$ that the economy is able to deliver. To me, there is something intuitively appealing about defining "sustainability" to be the time-weighted average of future consumption possibilities, where the "weight" is the equilibrium discount rate on consumption that the actors in the economy themselves are displaying.[6] Note that the annualized equivalent consumption flow used here to define sustainability is a *hypothetical* level that may not actually be attainable.

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[6] I realize that there is an extensive literature on the appropriate social discount rate, which represents a set of issues I am sidestepping here. If the appropriate discount rate is different than the competitive own rate of return on consumption, then in principle the formulas of this paper could all be redone using corresponding shadow or efficiency prices — although I would hate to be the one who has to make such recalculations in practice.

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From the above definition, sustainability at time t, denoted $\Psi(t)$, is given by the formula:

$$\Psi(t) \equiv r \int_t^{\infty} C^*(s)\, e^{-r(s-t)}\, ds. \tag{13}$$

In this context, the phrase "sustainable development" might be interpreted to mean a trajectory along which

$$\Psi(t) \geq C^*(t) \tag{14}$$

for all t.

In conformity with the symbolic notation previously introduced, $[C^*]$, defined by (12) above for $X(t) = C^*(t)$, denotes the economy's sustainability at the current time zero, or:

$$\Psi(0) = [C^*]. \tag{15}$$

Let $Y^*(t)$ denote inclusive or Green NNP at time t. Then:

$$Y^*(t) = C^*(t) + \mathbf{P}(t)\dot{\mathbf{K}}^*(t) = G(\mathbf{K}^*(t), \mathbf{P}(t), t). \tag{16}$$

The principal task of this paper is to elucidate the relationship between $\Psi(t)$ and $Y^*(t)$. Strictly for notational ease and without loss of generality we choose to perform the evaluation at the present time $t = 0$, so that we will be comparing $\Psi(0)$ with $Y^*(0)$.

To this end, we must define the following two summary statistics of relevant growth rates:

$$g \equiv \frac{[\dot{Y}^*]}{[Y^*]} \tag{17}$$

and

$$\lambda \equiv \frac{[\partial Y^*/\partial t]}{[Y^*]} \tag{18}$$

where $\partial Y^*/\partial t$ denotes $\partial G/\partial t$.

The summary growth statistic g is interpretable as an expression of the average future growth rate of Green NNP. The summary growth statistic λ is an expression of the average future growth rate of the "residual", which captures the pure effect of time alone on enhancement of productive capacity not otherwise attributable to capital accumulation.[7]

[7] It is theoretically possible that λ could be negative for some situations. For example, an exporting country facing declining terms of trade over time might have a negative value of λ if the time-deteriorating terms-of-trade effect has a strong enough economic impact.

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To understand better the meaning of definitions (17) and (18), rewrite them as:

$$\int_0^{\infty} (\dot{Y}^*(t) - gY^*(t))\, e^{-rt}\, dt = 0 \tag{19}$$

and

$$\int_0^{\infty} \left(\frac{\partial Y^*}{\partial t}(t) - \lambda Y^*(t) \right) e^{-rt}\, dt = 0. \tag{20}$$

Conditions (19) and (20) make clear the sense in which g and λ can be interpreted as weighted average growth rates of, respectively, aggregate output and the "residual". Consider, for example, (19). The weighted amount by which $\{\dot{Y}^*(t)\}$ exceeds $\{gY^*(t)\}$ over time is exactly equal to the weighted amount by which $\{gY^*(t)\}$ exceeds $\{\dot{Y}^*(t)\}$ over time, where the weighting factor at time t is, naturally, chosen to be $\{e^{-rt}\}$. Likewise for $\partial Y^*/\partial t$ and λY^* in (17).

The main use of (17) and (18) will ultimately be to treat g and λ as parametrically given projections of average future growth rates in order to analyze the relationship between sustainability and current Green NNP, and to understand better what critical features of the growth path it depends upon. For this purpose of performing sensitivity analysis, the proposed definitions (17) and (18) are more than adequate representations of the underlying concepts behind projected values of g and λ. Note that in the special case of steady exponential growth, definitions (17) and (18) reduce to the underlying constant rates of growth exactly.

The primary aim of the present paper is to determine the degree to which current inclusive or Green NNP, $Y^*(0)$, reflects future sustainability, $\Psi(0)$, in the presence of technological progress. Let Θ stand for the appropriate "technological progress premium" needed to convert $Y^*(0)$ accurately into $\Psi(0)$. By definition, the correction factor Θ satisfies the condition

$$\Psi(0) = Y^*(0)[1 + \Theta]. \tag{21}$$

The main result of the paper is the following formula (22).

Theorem. *Under the assumptions of the model, the appropriate technological progress premium is*

$$\Theta = \frac{\lambda}{r - g}. \tag{22}$$

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IV. Proof of the Main Proposition

In the proof, algebraic manipulations are compressed to save space. To keep the proof simple, I assume that any relevant variables are time-differentiable almost everywhere on $t \in [0, \infty)$.

Taking the total time derivative of $Y^*(t) = G(\mathbf{K}^*(t), \mathbf{P}(t), t)$ along an optimal trajectory,

$$\dot{Y}^*(t) = \sum_{j=1}^{n} \frac{\partial G}{\partial K_j} \dot{K}_j^* + \sum_{j=1}^{n} \frac{\partial G}{\partial P_j} \dot{P}_j + \frac{\partial G}{\partial t}. \tag{23}$$

From (3), (6) and the theory of cost functions[8] it follows that along an optimal trajectory the following duality conditions must be satisfied for all j:

$$\frac{\partial G}{\partial P_j} = \dot{K}_j^*. \tag{24}$$

Substituting from (24) and (7) into (23), and canceling out terms of the form $\Sigma \dot{P}_j \dot{K}_j^*$, yields along an optimal trajectory the equation:

$$\dot{Y}^*(t) = r \sum_{j=1}^{n} P_j \dot{K}_j^* + \frac{\partial G}{\partial t}. \tag{25}$$

By substituting from (16), expression (25) becomes equivalent to

$$\dot{Y}^*(t) = r(Y^*(t) - C^*(t)) + \frac{\partial G}{\partial t}. \tag{26}$$

Applying the stationary-equivalence operator (12) to (26) transforms it into the equation

$$[\dot{Y}^*] = r([Y^*] - [C^*]) + \left[\frac{\partial Y^*}{\partial t}\right]. \tag{27}$$

Substituting from (17), (18) into (27) turns it into the condition

$$g[Y^*] = r([Y^*] - [C^*)]) + \lambda[Y^*], \tag{28}$$

which can be rewritten as

$$[C^*] = [Y^*] \left(\frac{\lambda + r - g}{r}\right). \tag{29}$$

[8] See footnote 9 in Weitzman (1976).

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Equation (29) relates $[C^*]$ to $[Y^*]$. Now, essentially, what remains to be done is to determine the relation between $[Y^*]$ and $Y^*(0)$.

Towards that end, a mechanical integration by parts of the integral form $\int re^{-rt}\dot{Y}^*\,dt$ ($= \int u\,dv$, where $u \equiv r\,e^{-rt}$, $dv \equiv \dot{Y}^*\,dt$) yields the expression

$$[\dot{Y}^*] = -rY^*(0) + r[Y^*]. \tag{30}$$

Substituting from (17) into (30) to eliminate $[\dot{Y}^*]$ gives the desired relation:

$$[Y^*] = Y^*(0)\left(\frac{r}{r-g}\right). \tag{31}$$

Now, finally, using (31), substitute for $[Y^*]$ in (29) and rearrange terms to get

$$[C^*] = Y^*(0)\left(1 + \frac{\lambda}{r-g}\right). \tag{32}$$

The above expression (32) is equivalent to (22), thus concluding the proof. □

Note that the basic result of Weitzman (1976) — when technology is independent of time, $\Psi(0) = Y^*(0)$ — corresponds here to the special case of (32) where $\lambda = 0$.

V. Conclusions

If we think generally of Θ as a parameter quantifying the appropriate "technological progress premium", then how might this parameter best be estimated? However imperfect it might be, as a practical matter we have a better intuitive feeling for projecting future rates of the "Solow residual" than for forecasting the relevant future parameter values or functional forms of any existing model of endogenous growth theory. If we go the route of this paper, then we have a methodology for estimating Θ and can at least hope that it could be a decent approximation for what might also be derived from the "right" form of a more-fully-specified model where innovation and externalities are endogenously determined.[9]

Suppose that defensive environmental spending in an advanced industrial economy such as the United States can serve as a very rough measure of the welfare loss of the negative environmental externalities it is

[9] For an example of a model in the spirit of endogenous growth theory being used to address issues of social accounting and welfare measurement, see Aronsson and Löfgren (forthcoming).

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intended, in part, to offset.[10] The total "cost of a clean environment" is currently estimated to be about 2% of GNP.[11] As for the depletion of natural capital like subsoil minerals, forests, or topsoil, this is currently a negligible fraction of national product in the United States.[12] To a tolerable degree of approximation, then, it becomes difficult to argue that making all the proper adjustments for depleted natural resources and deteriorated environmental assets might bring conventionally measured NNP down by more than about a couple of percentage points when it is converted over to Green NNP.[13]

What about the upward adjustment of NNP indicated by the "technological change premium"? In this case, formulas (21), (22) give some handle on the theoretically appropriate relationship between (future) sustainability and (present) inclusive NNP. Here, it seems that the correction factor is considerably larger, perhaps an order of magnitude greater. As very rough estimates, suppose the following numbers are chosen[14]:

$r = 5\%$ = annual after-tax real return on capital
$g = 2.5\%$ = annual real growth rate of NNP
$\lambda = 1\%$ = annual growth rate of total factor productivity

With these numbers,[15] the technological change premium is $\Theta = 40\%$.

A warning is in order about this kind of exercise. First of all, it is undertaken in what might be called a "command optimum", presuming that negative and positive externalities are internalized in an optimal manner. Second, some very rough ballpark numbers that, at best, apply only to the present situation are being extrapolated far forward as presumptive forecasts.

No one should feel fully at ease projecting such crude estimates as have been made above onto an indefinite future. And, of course, Θ will change with different assumed values of the underlying parameters. Yet, when all is said and done, I believe it is fair to say that a reasonable parametric

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[10] I realize that several important issues are being glossed over here, but it is only the approximate magnitude of this number that matters in the present context.

[11] See EPA (1991).

[12] See U.S. Commerce Dept (1994, p. 15).

[13] See the appropriate section of Weitzman and Löfgren (forthcoming) for a more exact description of the relevant calculation. For the purposes of this paper, it does not matter if the correction in the text above is off by a factor of two.

[14] Such numbers could be justified by reference to e.g. Jorgenson (1994), BLS (1994) and Nordhaus (1995).

[15] Note that it makes no difference whether the calculation is done on a per capita basis or, as here, on a total basis, because the numerator λ and the denominator $(r-g)$ of the formula (22) for Θ are invariant to such an alteration.

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analysis done on (21) seems to make the following conclusion hard to resist:

"Sustainability" would appear to depend more critically on future projections of the residual than on the typical corrections now being undertaken in the name of green accounting. Because it omits the role of technological progress, NNP, whether conventionally measured or green-inclusive, likely understates an economy's sustainability.

The ultimate origins of the "residual" are still poorly understood by economists. But if future growth rates of technological progress resemble those of the past, we are probably underestimating significantly an economy's future power to consume when we identify it with current NNP, however inclusive that measure is made.

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