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Methodological and Ideological Options

Toward a neoclassical theory of sustainable consumption: Eight golden age propositions

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ABSTRACT

Popular trends in ecological economics increasingly consign neoclassical economics to the sidelines of modern-day relevancy. The neoclassical tradition is often seen as reliant for its authenticity on a presumption of human avarice – both unbridled consumerism and corporate cupidity – and demanding for its real-world applicability an assumption of continuous economic growth in a world of hard limits.

This article examines the question of whether neoclassical theory could instead provide keys to deeper understanding of sustainable consumption. By combining in a single framework neoclassical growth theory, general equilibrium theory and duality theory – and by explicitly considering leisure time – the analysis demonstrates that neoclassical economics yields several useful insights bearing on long-term sustainability. The analysis confirms several tenets of ecological economics and challenges others.

Eight propositions emerge from this analysis that could help speed the development of a robust neoclassical theory of sustainable consumption, here branded "golden age" propositions as they strongly echo the "Golden Rule" discoveries of Edmund Phelps.

1. Introduction

It is currently popular among a growing number of ecological and sustainability economists to dismiss neoclassical economics for its apparent sanctifying and legitimizing of corporate and consumer cupidity and a seeming requirement for its validity of unbridled never-ending growth.

This article seeks to help rehabilitate this image neoclassical economics has fallen victim to. In fact, it will be claimed that a world of sustainable consumption requires all the trappings of a competitive private ownership economy, including producer profit-maximizing behavior and consumer utility-maximizing behavior. And that neoclassical economics is indispensable to a correct understanding of a sustainable world.

The history of this evident disconnect is revealing. In a vigorous and entertaining debate found in the early pages of the present publication, Herman Daly (1997) used the device of appealing to the work of Georgescu-Roegen (1975, 1979) to challenge leading neoclassicists Robert Solow and Joseph Stiglitz on the fundamental underpinnings of their conception of economic growth. Solow (1997) and Stiglitz (1997) responded in a manner befitting the neoclassical tradition they helped create, but left unaddressed key issues raised by Herman Daly (1997). Robert Ayres (1997), in the same issue, offered a very precise, even surgical, dissection of the strengths and limitations (mostly strengths) of Georgescu-Roegen's arguments.

While at first brush these two camps may appear to hold virtually irreconcilable positions, this paper seeks to present a more robust neoclassical response to Herman Daly (1997) that purports to show that in fact both camps present valid arguments — and indeed may not be as far apart as some appear to believe.

In particular, it will be shown that a more comprehensively-conceived neoclassical formulation of sustainable consumption opens the door to a deeper understanding of the following: the prospect of indefinitely-extended fixed consumption levels; the prospect of natural "golden rule" consumption paths (in the Phelps sense) having not only indefinitely-extended fixed consumption levels, but ever-declining resource use and ever-increasing levels of leisure time; the sustainability implications of limited and depleting natural resource stocks; poverty elimination and consumption trends; and the surprising and counterintuitive effect of improvements in natural resource use efficiency gains. It is further shown that the framework delivers results that are in many ways confirmatory of the ecological economics tradition but in other ways challenge it.

2. Background

Given this heroic objective of marrying neoclassical economics to ecological economics, the theoretical framework here offered must by necessity call upon principles and methods developed by neoclassical

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researchers in four different realms. To help assuage the concerns of the skeptic, the following descriptions attempt to highlight their commonsensical foundations:

First, general equilibrium theory: The framework relies heavily on the work of Gerard Debreu and Kenneth Arrow (Arrow and Debreu, 1954), who importantly and famously demonstrated that a competitive private ownership economy will naturally tend to evolve toward an equilibrium where all markets clear at prevailing prices using profit-maximizing and utility-maximizing principles in a way that maximizes economic welfare. In this world, individuals own the means of production and command the labor they offer to producers. The first of these is via the investments they (or their household) make, meaning the capital existing in the economy is in their hands. More importantly for present theoretical framing purposes, so is their choice over how much of their time they will allocate to producers, and how much to reserve as leisure time. General equilibrium provides a natural framework, and justification, for explicitly considering leisure time as a quantity in a general utility function.

Second, neoclassical growth theory: With insights about sustainable consumption economics the primary goal, the framework clearly must consider the long-term evolution of an economy. Fortunately, Robert Solow in 1956, working from a thorny conundrum that had plagued previous growth theorists, created a framework that both solved the problem and delivered important new insights about the nature of economic growth and the role of technology in creating it (Solow, 1956, 1988). For purposes of the present framework, the key implication is that long-term dynamics must be represented in a way that conforms to the principles and methods of neoclassical growth economics, including explicit consideration of technology gains.

A benefit follows from this. Of specific importance to the neoclassical growth theory is the work of Edmund Phelps, who established a central result known as Phelps' Golden Rule of Accumulation (Phelps, 1961, 1965). The present analysis shows that combining the general equilibrium piece with the neoclassical growth piece delivers substantial confirmation of Phelps' Golden Rule and leads to a modest extension of it.

Third, duality theory: To unite the production side and household consumption side of the economy, and to be consistent with both general equilibrium theory and neoclassical growth theory, physical quantities must be accompanied by their prices. Ronald Shephard in 1953 and later in 1970 developed the foundation for duality theory (Shephard, 1953, 1970), enhanced and made more broadly understood and accessible by Erwin Diewert (1974) and others in the decades thereafter. A proper framework must account for this tight connection, which as will be seen carries with it significant implications for consumption.

Fourth, neoclassical consumption theory: Neoclassical growth theory assumes a fixed-for-all-time relationship between savings and the productive value output of the economy (an assumption, it will be seen, that is generally warranted even within this extended framework). The rubric adopted by neoclassical consumption theorists is somewhat different. Specifically, the work of Franco Modigliani and his colleagues Richard Brumberg (Modigliani and Brumberg, 1954) and Albert Ando (Ando and Modigliani, 1963) on lifecycle consumption theory predicted that consumption behavior would depend not only on the value output of the economy, but also on the assets held by the household. The present framework instead shows that while household utility maximizing behavior delivers tight relationships between consumption/savings and both output and assets, these connections are delivered as a result, not an assumption, of the framework, thus explaining observed correlations.

Finally and not least, because a substantial part of the concept of "sustainable" is not only consumption itself but also the raw resource use required to enable it – including the associated externalities and limitations of such in the present-day world – the framework embodies on the productive side of the economy explicit consideration of this key input to production.

With these concepts in hand and attended to, a framework to address the notion of sustainable consumption from a neoclassical economics perspective can be assembled.

For theorists, four primary technical contributions purporting to be offered in the context of this growth framework are:

1. A broadening of the household utility function to include specific consideration of the value of leisure time.
2. Endogenization of savings behavior and resulting capital formation and endogenization of labor supply.
3. Explicit consideration of the duality principles that lock prices to physical quantities, allowing the system to be closed in a general equilibrium sense.
4. Formal consideration of physical resource use in the production of final goods and services (not in itself a new development, but new when introduced into such a framework).

The alleged overall technical contribution is the formal integration of these features into a framework that honors general equilibrium in each time period of a growth model: all factor markets (and the output market) clear at their endogenously-calculated prices each period; there is no need for labor or capital supply curves as labor supply and investment are determined endogenously from utility-maximizing behavior. The only exogenous inputs needed are the growth rate of the labor force (or population) and the physical deterioration rate of capital-in-place (depreciation rate).[1]

The article is organized as follows: The next section briefly describes the theoretical framework. The section thereafter outlines the simulation model, an instantiation of the theoretical frame in the form of specific functional representations of utility and production. After that, the resulting analytics are developed, leading to the proposed eight propositions offered in the section following thereafter. Then is offered a listing of cautions and limitations, followed by an attempt to re-cast the neoclassical–ecological economist debate in broader terms, and summarizing comments on the value of neoclassical economics to understanding sustainability. Appendices contain mathematical details.

3. Theoretical Framework — Briefly

The centerpiece of this article is a new theoretical framework purporting to integrate all the key neoclassical concepts relevant to a deeper evaluation of sustainable consumption, but as present readers may be disinclined toward neoclassical mathematics, a full description is left to online appendices, posted alongside this article.[2]

Nonetheless, to make sense of the results that follow, readers require a brief overview of the framework and the meaning of certain variables and parameters. More importantly, the following exposition is aimed at informing intuition and illustrating the commonsense foundations of

[1] That is, aside from any parameters associated with functional forms chosen for a utility function and a production function (including any technology change parameters employed).

[2] Notwithstanding this, the author eagerly welcomes reactions and criticisms to this formulation by neoclassical economists who, it is hoped, will engage the full formulation presented in the appendices.

what may otherwise appear to some as arbitrary mathematical constructs of neoclassical theory.

3.1. Households and Producers

In neoclassical economics, households make their choices and display their preferences by appealing to an underlying utility function. The household utility function is here taken to be a function that operates on three physical quantities – consumption, savings and leisure time – to deliver a measure of household satisfaction. Duality theory later allows us to incorporate consideration of associated prices. In particular, consumption C is taken to be the quantity of goods and services (expressed in some physical terms) used by the household in a given period. Likewise, leisure time l is considered to be defined in units of hours (or hours per time period). Savings S is considered to be equivalent to the quantity of physical production assets to which households newly claim ownership by investing savings of amount S (“real” savings, when duality conditions are considered). These combine to produce household satisfaction u as follows:

$$u = f(C, S, l). \tag{1}$$

Realizing maximum utility requires that households command externally-generated resources, resources that determine the budget available to them (derived in online Appendix A). Further, consumption (and savings) cannot occur without something physical being provided to the households. Physical consumption requires that the economy includes a productive sector, and households must supply that sector the necessary capital and labor resources. Again in standard fashion, this sector is represented with a production function, depicting the manner in which capital and labor supplied by households can be employed to produce consumable goods and services:

$$Y = g(K, L) \tag{2}$$

where Y is the physical quantity of goods and services that can be produced using the physical capital K and physical labor L supplied by households via their savings/investments and via their participation in the workforce. A key distinction is here made between the quantity of labor L households decide to contribute to production and the quantity of work hours theoretically available to supply it, $\overline{L}$, the difference being leisure time, $l = \overline{L} - L$. Economy-wide, this can be thought of as the distinction between the workforce employed and the available workforce. In this framing of labor employment, “full employment” means the number of hours per period households are willing to supply firms, with account taken of desired levels of leisure time (and human beings clearly need time to sleep, eat, etc.). The introduction of natural resources R into the framework is described below.

Both the utility function u and the production function Y describe sets of possibilities, not specific solutions, thus compelling consideration of agents' behavior. Specific solutions can be delivered by combining producer profit-maximizing behavior with household utility-maximizing behavior, described explicitly in online Appendix A.

Formally closing this system requires introducing duality principles in the form of endogenously-calculated prices for the physical variables so that markets all clear in a general equilibrium sense. As shown in online Appendix A, the price of capital r, the price of labor (or wage rate, w), and the price of output c are sufficient to achieve this, even considering that physical consumption, physical savings, and resources R must each carry a price. Further, it is shown that leisure time must carry a price and that this price is precisely w – the wage rate – and so the framework places implicit value on labor that creates economic value but is uncompensated, e.g., household operations and child care.

3.2. Neoclassical Growth Dynamics

Clearly time dynamics is central to an understanding of sustainable consumption. Further, account must be taken of the fact that physical assets in the form of human-fabricated capital deteriorate over time, absent some fanciful appeal of the laws of thermodynamics.

Neoclassical growth theory provides the natural means to examine evolution of the economy over periods spanning decades, the horizon of relevance to long-term sustainability.

The application of growth theory starts with the labor supply capacity $\overline{L}$ introduced above. In parallel with the standard framework, this capacity will grow over time at some “natural” rate n, so that:

$$\overline{L}_t = \overline{L}_0 e^{nt}. \tag{3}$$

In a slight departure from standard neoclassical growth theory, capital accumulation is here driven by household choices regarding savings according to their utility function (Eq. (1)). In any period, households contribute capital to production by forgoing consumption of some of the final output created by their capital and labor contributions and instead allow a portion of production to be directed to the creation of capital goods in the form of investment. Thus, investment in each period is:

$$I_t = S_t. \tag{4}$$

The resulting capital in place (and investment assets held by households) is calculated accounting for physical depreciation, δ. So in any one period capital in place is

$$K_t = (1-\delta)K_{t-1} + S_t. \tag{5}$$

At this point, the framework is essentially complete. Note that everything is endogenously-determined with the exception of the two exogenous parameters n and δ.

But to address the “sustainable consumption” question raised at the outset, two additional refinements require attention.

3.3. Refinement #1 — The Resource Sector

Much of what occupies the attention of ecological economists is the notion that the available raw resources that sustain economic activity are in many cases finite and exhaustible, living as we do on a spherical, geometrically-bounded planet. And further that their exploitation entails ever-greater assaults on the natural environment — the “natural capital” endowment that fundamentally enables human well-being.

In fact, a key contribution of ecological economics is the recognition, first brought to light by Georgescu-Roegen (1975, 1979) and developed in more explicit detail by Daly, that it is inadequate to consider resource flows through the economy alone, but that rather the stocks of natural resources must be simultaneously accounted for if the story is to be complete in any finite world. And that thermodynamic principles place stringent limits on human exploitation of those stocks.

Georgescu-Roegen and Daly have further argued that human-generated physical capital and raw resources (“natural capital”) are not ready substitutes for one another (as neoclassical economics seems to assume), but rather more closely resemble inputs complementary to one another — both are necessary. And that a continual flow of raw resources is needed to maintain any given level of economic activity.

To accommodate these ideas, the framework takes explicit account of raw resource use, first as a flow feeding production:

$$Y = g[X(K_X, L_X), R(K_R \cdot L_R)] \tag{6}$$

where K_R and L_R are the capital and labor allocated to the production of raw resources R that feed the production of intermediate goods and services X to deliver final output Y, while K_X and L_X are those feeding the production of intermediate goods and services directly. Capital and labor in both sectors contribute to the creation of final goods and services in a manner governed by the function g.

Three things to note about this formulation: One, depending on the nature of the function g (this is made more explicit in the following section), capital, labor and resources can indeed substitute among one another to a greater or lesser degree. This comprehends the positions of Solow (1997) and Stiglitz (1997), who each cite examples of such substitution in defense of this idea. But two, when combined with the neoclassical growth dynamics described previously, it becomes apparent that capital and resources are nonetheless clear complements in an entirely different sense — any expansion of capital employed, deriving from household investment sufficient to more than replace capital stock that has depreciated out of the system, will carry with it increased requirements for resources to make this capital productive, a feature in concert with the conceptual formulations of both Georgescu-Roegen and Daly. A portion of final output Y, it will be recalled, will be set aside by households for the creation of resource-using capital goods — not all of Y is consumed in any period. And three, it can be seen from Eq. (6) that the creation of this new capital itself entails the consumption of resources — capital has "embedded" in it the resources used to create it (as does all output Y of goods and services), a strong echo of the long-ago idea of "embodied energy" put forth by Robert Costanza (1980).

To comprehend the resource-as-stock question, declining technology parameters, later described, are applied to K_R and L_R to reflect the increasing difficulty (and cost) of exploiting depleting stocks of natural resources without damaging ecosystems. This is later used to explore the notion, advanced by both Georgescu-Roegen and Daly, that consumption – to be sustainable – must rely on ongoing "maintenance flows" of natural capital. As will be seen, the dynamics that emerge from this formulation closely mirror those reported by Kraev (2002).

As described in online Appendix B, the application of Shephard's Lemma, along with an assumption that capital and labor are fungible across these two sectors, allows us to preserve the integrity of a closed system, with only n and δ introduced exogenously.

3.4. Refinement #2 — Technology Gains

A central element of Robert Solow's astonishing contribution to our understanding was explicit consideration of the effects of technology gains. He, and others, recognized that no neoclassical theory could be explanatory of Nicholas Kaldor's "stylized facts of economic growth" (Kaldor, 1957) without acknowledging this.

Accordingly, a defensible framework must take account of this phenomenon. Specifically, the production function (Eq. (2)) should be specified as

$$Y = g(K, L, \boldsymbol{\tau}) \tag{7}$$

where $\boldsymbol{\tau}$ is a vector of technology parameters. In neoclassical growth fashion, these parameters are introduced as factor-augmenting technology gains.[3] This is a divergence from the approach adopted by ecological economists such as Robert Ayres, who famously and properly introduced the idea that economic growth is fueled in large part by efficiency gains in the use of exergy (e.g., Ayres and Warr, 2005), which he claims better explains Kaldor's "growth gap" than do factor-augmenting technology gains, and importantly is more consistent with thermodynamic principles. However, honoring the neoclassical formulation of the present framework requires the factor-augmenting approach, as the production function adopted by Ayres and Warr (an adaptation of the LINEX function developed by Kümmel et al (1985)) violates neoclassical principles.[4]

In the next section this vector $\boldsymbol{\tau}$ is specified more precisely for the present analysis, but with its introduction, we now have a complete neoclassical specification.

Unfortunately, this is about as far as the theoretical framework itself will take us in exploring the question of sustainable consumption. Owing to the rich diversity of variable interactions, analytic conditions readily derivable from the framework are complex and decidedly miserly in the insights they offer.[5] While nimbler minds may do better, the development here is reduced to working with specific functional forms, and what may be worse, exploring what a simulation model has to tell. That said, the simulation model is an exact implementation of the theoretical framework's equations, with no added or hidden assumptions beyond a specific parameterization of the functional forms based largely on the econometric measurements of Stern and Kander (2012) for Sweden.

4. The Simulation Model — Briefly

Simulations in the following sections employ a utility function of the Cobb–Douglas form:

$$u(C, S, l) = u_0 C^{\gamma} S^{\nu} l^{1-\gamma-\nu}. \tag{8}$$

While more sophisticated functional forms are often used, this form has the advantage that the exponents of C, S, and l denote households' preferred shares of consumption, savings, and leisure time, thus informing intuition in the results that follow. Note that it is a constant-returns-to-scale function, indicating that households' utility neither saturates nor accelerates when the three components rise in lock-step.

The production function is chosen to reflect common usage in neoclassical growth theory. In particular, the framework employs an extended version of Solow's so-called CES (constant-elasticity of substitution) production function:

$$Y = \left\{ a\left[\left(\tau_{K_X} K_X\right)^{\alpha} \left(\tau_{L_X} L_X\right)^{1-\alpha} \right]^{\rho} + (1-a)\left[\tau_R \left(\tau_{K_R} K_R\right)^{\beta} \left(\tau_{L_R} L_R\right)^{1-\beta} \right]^{\rho} \right\}^{1/\rho}. \tag{9}$$

Here there are two sectors, where K_R and L_R are the capital and labor allocated to the production of raw resources R that feed the production of intermediate goods and services X to deliver final output Y, and K_X and L_X are the capital and labor allocated to the production of intermediate goods and services themselves. Specifically, intermediate goods and services are produced by using the quantities of capital and labor allocated to this sector so that $X = \left(\tau_{K_X} K_X\right)^{\alpha} \left(\tau_{L_X} L_X\right)^{1-\alpha}$ and likewise raw materials are produced in the physical quantity $R = \left(\tau_{K_R} K_R\right)^{\beta} \left(\tau_{L_R} L_R\right)^{1-\beta}$. R is the quantity of raw resources that can be provided to the intermediates sector using the quantities of capital and labor K_R and L_R. Final goods and services are created by combining X and R according to Eq. (9).

The parameters τ_{K_X} and τ_{L_X} are factor-augmenting technology gains associated with capital and labor in the intermediates sector, and τ_{K_R} and τ_{L_R} are those that apply to the extraction of raw resources. If raw resources are exhaustible, and/or require ever-greater effort and cost to

[3] Modern advances in neoclassical theory seek to treat technology gains as endogenously-determined, (see Romer, 1990). This extension of the theory is not here considered. Instead, this article restricts itself to exploring macro effects of technology gains while remaining agnostic as to their provenance. This is a restriction that needs to be examined in future research.

[4] This function is not concave as it shows increasing rather than diminishing marginal productivity of labor, a feature most neoclassical economists would reject, and one that potentially skews the Ayres–Warr results (see Saunders, 2008, Proofs Appendix F, Lemma 2 for a proof of this limitation of the LINEX function).

[5] For instance, an initial goal of this article was to develop an analytic expression for sustainable consumption of the form $\frac{dC}{dt} = 0$. However, the resulting expression is, while accurate (one hopes), an unholy mess.

exploit in an environmentally-prudent way, these latter parameters can decline with time reflecting the need for ever-more capital and labor to produce any given unit of physical resources delivered to producers and households.

The parameter τ_R depicts the potential for the intermediates sector to require fewer raw resources for a fixed level of production owing to efficiency gains in their use (in the energy economics literature, this is commonly described as the "energy efficiency" parameter). The quantity $\tau_R R$ can be thought of as the "effective" use of physical resources in production. This parameter τ_R will become useful when we examine how resource efficiency-in-use improvements affect resource use. All technology parameters are of the form $\tau_i = \tau_0 e^{\lambda_i t}$, where the λ_i is assumed to be fixed percentage gains per period.

The parameter ρ accounts for the elasticity of substitution between raw resources and intermediates, with $\rho = (\sigma - 1)/\sigma$ and σ being the elasticity of substitution.

In the simulation model, all production function parameters, depreciation rate δ, and initial values of the variables are set to roughly match values reported by Stern and Kander (2012) for Sweden, measured over a 150 year historical interval.

Generating the required prices necessitates employing the specific unit cost function that is dual to the production function (Eq. (9)), derived in online Appendix B.

The simulation model is posted online alongside this article. It is user-friendly and allows the user to explore the effects of changing various parameters and assumptions.

5. Sustainable Consumption Explorations — No Technology Improvements

For ease of exposition and developing understanding, it is convenient to begin by assuming an economy in which technology is frozen at current levels indefinitely. This also enables better understanding of the role of technology in changing this section's conclusions about sustainable growth when it is introduced in the next section.

5.1. The Role of Population Growth

Simulations reveal that whether or not the available labor force (population) is growing, the economy naturally gravitates toward a highly stable growth condition[6]:

Table 1 shows that under conditions of zero population growth[7] and the absence of new technologies, the economy naturally gravitates toward a condition of fixed consumption level (C). In a departure from the speculations of Herman Daly (2005, 2008), real returns to capital (r/c) do not fall from the levels they realize when population (and consumption) is growing. Also, the economy moves to a condition of full employment (in the sense that households realize an allocation between labor supplied and leisure time that exactly matches their preferences), overcoming a problem Daly has expressed concern about (Daly, 2005, 2008). Even with zero growth of the economy, households deliver, according to neoclassical theory, the capital and labor inputs needed by producers to produce output sufficient to sustain consumption and leisure time at whatever level is desired by households according to their utility preferences. In other words, perpetual growth is not a requirement of the theory, unlike what some have claimed.

Table 1
Growth paths with and without population growth.

—	Zero Growth in Labor Force		1% Annual Growth in Labor Force	
	Value in Per>od 100*	Growth rate	Value in Perod 100*	Growth rate
u	1.00	0.00%	2.70	1.00%
C	0.75	0.00%	2.C1	1.00%
S	0.25	0.00%	0.67	1.00%
/	2.00	0.00%	5.44	1.00%
Y	1.0C	0.00%	2.68	1.00%
K	1.00	0.00%	2.58	1.00%
L	1.00	0.00%	2.72	1.00%
R	0.18	0.00%	0.47	1.00%
C	1.00	0.00%	1.00	0.00%
w	0.75	0.00%	0.75	0.00%
r	0.25	0.00%	0.25	0.00%

* NormaUzed values

But as seen, neoclassical theory given these assumptions predicts consumption and resource use will increase in lock-step with population growth if the labor force grows correspondingly. Utility, leisure time, and the other physical measures grow at the same rate as the population, meaning that they stay fixed on a per worker (per capita) basis.

Of course, even in the zero-growth case, fixed consumption levels are not a prescription for sustainability — fixed consumption is not automatically sustainable if it draws on limited stocks of raw resources. One can think of this as a hypothetical world in which energy resources are supplied in a way that makes them clean and indefinitely renewable. And it is a world wherein all other raw materials are provided in a way that makes them perfectly recyclable. Naturally, unless such materials are somehow derived from renewable biological sources, such a world will be in violation of thermodynamic principles, or at least dependent on ever-increasing supplies of renewable energy to overcome increasingly-stringent thermodynamic limitations on recycling, but forgoing consideration of this for the moment is justified by the additional results delivered.

5.2. Phelps' Golden Rule

The additional results are noteworthy. Despite its departure from standard neoclassical growth theory, the framework delivers what Edmund Phelps calls "golden age paths," and in specific circumstances (to be described shortly) delivers behavior that exactly matches Phelps' Golden Rule (Phelps, 1961, 1965).

Even though household choices regarding savings and consumption do not derive from some fixed relationship to any variable of economic activity such as the value output of the economy or the assets held by households, the result is that savings, consumption, capital (household investment assets), output/income, labor and leisure all grow at the same rate — definitional of a "golden age path." Further, nominal wages and nominal returns to capital likewise remain stable and fixed and so therefore does the household budget. The nominal price of output stays fixed.

In the zero-growth case, the realized level of fixed consumption is determined by the parameters of the utility function. This is illustrated by examining the sensitivity of results to the savings parameter ν:

Table 2 shows the long-term equilibrium values of utility function variables attained by the system when varying the utility function parameter ν. These are all "golden age" trajectories by the Phelps definition as all variables "change (if at all) at a constant relative rate" (Phelps, 1965). Not shown, but also meeting this condition are the production-side variables Y, E, K_X, K_R, L_X, L_R, R, w, r, and output price c for all paths.

[6] The simulation results reported in this and the following section derive from a 100-period dynamic simulation, though convergence to a stable growth condition generally occurs within 10 periods or less.

[7] Despite being a borderline impetuous departure from best practice in economics, it is intellectually intolerable to not cite a compelling recent result from evolutionary biology that bears directly on this assumption. Specifically, Gavrilov and Gavrilova (2010) have proved that even were the human population to achieve immortality (in the specific sense of achieving non-senescence wherein individuals can die only of so-called "extrinsic" causes – as a result of accident, predation, starvation, environmental assault or disease – but never of aging), the human population would asymptotically approach some fixed and insuperable level provided birth rates were limited to less than 2.0 offspring per female. In other words, the medical defeat of senescence would still permit perpetual generation of children without surpassing some limited planetary population. This is a remarkable result.

Table 2
Golden age growth paths as a function of the savings parameter ν.

						Phelps Golden Rule condition*							
						Growth rate condition		Savings rate condition		"Consume your wages/save your returns"			
	ν	c	S	/	u	Actual	Real "social" return	Actual	Phelps' Golden Rule	Actual real wages, wL/c	Consumption, C	Actual real returns, rK/c	Savings, S
	0.20	0.90	0.60	1.71	0.947	0.00%	−9.37%	0.40	0.25	1.13	0.90	0.38	0.60
Golden Rule path	**0.10**	**0.75**	**0.25**	**2.00**	**1.000**	**0.00%**	**0.00%**	**0.25**	**0.25**	**0.75**	**0.75**	**0.25**	**0.25**
	0.09	0.73	0.22	2.03	1.008	0.00%	2.08%	0.23	0.25	0.71	0.73	0.24	0.22
	0.03	0.70	0.19	2.06	1.017	0.00%	4.69%	0.21	0.25	0.67	0.70	0.22	0.19
	0.07	0.68	0.16	2.03	1.026	0.00%	3.04%	0.19	0.25	0.63	0.63	0.21	0.16
	0.06	0.65	0.13	2.11	1.035	0.00%	12.50%	0.17	0.25	0.53	0.65	0.19	0.13
	0.05	0.61	0.10	2.14	1.043	0.00%	18.75%	0.14	0.25	0.54	0.61	0.18	0.10
	0.04	0.57	0–08	2.16	1.050	0.00%	28.12%	0.12	0.25	0–49	0.57	0.16	0.08
	0.03	0.53	0.05	2.19	1.054	0.00%	43.75%	0.09	0.25	0.43	0.53	0.14	0.05
	0.02	046	0.03	2.22	1.051	0.00%	75.00%	0.06	0.25	0.37	0.46	0.12	0.03
	0.01	0.37	0.01	2.24	1.024	0.00%	168.75%	0.03	0.25	0.29	0.37	0.10	0.01
	0.001	0.17	0.00	2.27	0.858	0.00%	1856.25%	0.00	0.25	0.13	0.17	0.04	0.0006

Not surprisingly as ν goes down so does savings S; consumption C likewise goes down as the economy has less capital with which to feed consumption; but leisure time increases to partly compensate, and so utility does not suffer as it would were leisure time not considered.

Varying the consumption parameter γ likewise has interesting effects. In this case, a reduction in γ delivers a utility-optimizing golden age path where consumption C goes down, but savings S and leisure time l go up. Increased savings can in effect be used to enable a sustainable increase in leisure time.

As shown, only one of these paths is a "Golden Rule" path by Phelps' definition (highlighted). Phelps specifies three conditions that must be met, indicated in the right-hand columns of Table 2. (These conditions are described and further analyzed in the present context in online Appendix C.) The distinction here is that while Phelps' Golden Rule delivers the maximum consumption level possible for the present and all future generations, the "golden age" paths of Table 2 each deliver the maximum utility level possible for the present and all future generations given household preferences.[8] In this way, all the paths of Table 2 are "Golden Rule" paths in the broader sense.

The two different definitions of "Golden Rule" pathways match only under particular conditions. If it happens to obtain that household utility function parameters are such as to precisely match the "natural" levels of capital and labor requested by the productive economy, the result will be a "golden age path" that further satisfies the Phelps' conditions that deliver Golden Rule behavior. This is illustrated in Table 3 — where unlike in Table 2 where production technology was held fixed and the utility function was allowed to change, in this table the utility function is held fixed and production technology is allowed to change by varying the parameter α:

As further described in online Appendix C, the Phelps consumption-maximizing Golden Rule and the utility-maximizing Golden Rule are identical under the following condition (given the specific functional forms employed here — a Cobb–Douglas utility function and a CES (Solow)-style production function):

$$\alpha = \frac{\nu}{\nu + \gamma}. \tag{10}$$

As α[9] is usually treated as a "natural" share of capital in use for production, so too the right-hand side of Eq. (10) can be considered a "natural" share of savings when choosing between savings and consumption. (It is only these two, not leisure, that rely on income produced from sources external to the household.) So the right-hand side of Eq. (10) is the share of earnings dedicated to savings. This is effectively the same thing as called for in Phelps' first Golden Rule condition given in online Appendix C, where the savings share is made equal the capital value share. So, not surprisingly, Phelps' consumption-maximizing Golden Rule holds under the conditions he specified.

This all leads to the possibility of a modest re-casting of Phelps' Golden Rule. That is, in accord with his famous proof that "do unto others [i.e., future generations] as you would have them do unto you," was a natural result of consumption-maximizing neoclassical growth theory, we can re-cast Phelps' formulation as a natural result of utility-maximizing neoclassical theory.

In other words, the spirit of Phelps' Golden Rule could be said to be achieved by households acting to maximize utility for the current generation, with consumption level being one component of this. Following this rule, households deliver, according to neoclassical theory, the inputs needed by producers to produce, sufficient to sustain consumption and leisure time at whatever level is desired by households according to their utility preferences. It is a utility-based Golden Rule.

The spirit of Phelps' Golden Rule could also be said to be met in its specifics, in the sense that Phelps' three conditions are mimicked by the conditions of equations A.4 and A.6 of online Appendix A, even if the conditions do not precisely match Phelps' conditions except where consumption maximization corresponds with utility maximization.

But the central conclusion is that sustainable consumption, in the sense of a consumption path fixed for all time, is both allowed and called for by neoclassical economics in a world of no technology improvements and zero population growth. And happily, the golden age paths delivered by theory are utility-maximizing for the current and all future generations, even while consumption stays fixed.

5.3. The Problem of Poverty

In today's world, the robust growth of developing nations is very like what the neoclassical growth model predicts. This carries with it a challenge inasmuch as it portends an increase, not a decrease, in consumption levels; and with that an increasing burden on the global environment, a concern of many ecological economists.

[8] It is important to realize that the utility u showing in Table 2 is the utility calculated from different preference functions (the utility function parameter ν is changing) and so technically the numbers are not comparable in a cardinal sense. Each in theory represents a separate utility function that is being maximized. However, it is important to recognize that a more sophisticated utility function can depict utility as a function of absolute parameter magnitudes, which can be emulated by a time-dependent evolution of function parameters while still respecting cardinality — a feature exploited in a later section.

[9] In this simulation, α is set equal β and so reflects the equilibrium value share of capital economy-wide.

Table 3
Golden age growth paths as a function of the production parameter α.

						Phelps Golden Rule conditions							
						Growth rate condition		Savings rate condition		"Consume your wages/save your returns"			
	α	C	S	/	u	Actual	Real "social" return	Actual	Phelps' Golden Rule	Actual real wages, wl/c	Consumption, C	Actual real returns, rK/c	Savings, S
	0.40	0.32	0.03	2.32	0.926	0.00%	85.00%	0.09	0.40	0.21	0.32	0.14	0.03
	0.30	0.45	0.05	2.23	1.016	0.00%	57.50%	0.09	0.30	0.35	0.45	0.15	0.05
	0.25	0.53	0.05	2.19	1.054	0.00%	43.75%	0.09	0.25	0.43	0.53	0.14	0.05
	0.20	0.60	0.06	2.15	1.088	0.00%	30.00%	0.09	0.20	0.53	0.60	0.13	0.06
	0.10	0.75	0.07	2.08	1.144	0.00%	2.50%	0.09	0.10	0.74	0.75	0.08	0.07
Golden Rule Path	0.09	0.76	0.08	2.07	1.149	0.00%	0.00%	0.09	0.09	0.76	0.76	0.08	0.08
	0.05	0.82	0.08	2.04	1.168	0.00%	−11.25%	0.09	0.05	0.86	0.82	0.05	0.08
	0.04	0.84	0.08	2.04	1.172	0.00%	−14.00%	0.09	0.04	0.89	0.84	0.04	0.08
	0.03	0.85	0.09	2.03	1.176	0.00%	−16.75%	0.09	0.03	0.91	0.85	0.03	0.09
	0.02	0.87	0.09	2.02	1.181	0.00%	−19.50%	0.09	0.02	0.94	0.87	0.02	0.09
	0.01	0.88	0.09	2.02	1.185	0.00%	−22.25%	0.09	0.01	0.96	0.88	0.01	0.09
	0.001	0.898	0.090	2.011	1.188	0.00%	−24.73%	0.09	0.00	0.99	0.90	0.00	0.0898

Yet to most development economists, "sustainable consumption" cannot be considered an ethically superior condition if it ignores the present-day reality that large populations of the planet suffer from an inability to realize consumption levels that are remotely sufficient to sustain them in any humane way. Development economists have for decades confronted and wrestled with this issue.

The only thing the present framework can offer in this connection is confirmation that neoclassical economics reveals a natural tendency for a neoclassical economy to correct for a situation of capital poverty, automatically gravitating toward a condition where labor force availability and capital availability come into balance. This is shown in Figs. 1 and 2.

As seen in Fig. 1, if one initiates the simulation model in a condition of under-capitalization and under-employment in the economy (i.e., initial capital at half the golden age path value; labor at 1.50 times its golden age path value), the economy nonetheless converges automatically to a condition of adequate capital supply and full employment — where here "full employment" includes consideration of individuals' utility for leisure time. To underline the benefits delivered by such convergence, it can be seen in Fig. 2 that the household utility realized by a capital-poor economy eventually matches that of an economy where golden age utility-maximization prevails:

This is simply a further reflection of the welfare-maximizing behavior found in an Arrow–Debreu economy.

5.4. The Problem of Exhaustible Resources

The final step before introducing technology gains is to see what the framework says about an economy on a fixed consumption trajectory but facing exhaustion of its primary raw resources.

If resources are exhaustible, they require increasingly greater effort to extract and supply to economic production. From Eq. (9), this will be reflected as a decrease in the effectiveness of capital and/or labor applied to the raw resources sector. Assuming 1% annual declines of capital- and labor-augmenting technology gains applied to resources extraction in place of fixed technology (i.e., $\lambda_{K_R} = -1\%$ so that $\tau_{K_R} = \tau_0 e^{\lambda_{K_R} t}$ is declining and no longer $=1$; and likewise $\lambda_{L_R} = -1\%$) has the following impact on future utility and consumption levels (Table 4).

This result is highly reminiscent of the results derived by Kraev (2002), despite the fact that the substitution possibilities it employs between natural resources and human-created economic inputs are considerably more aggressive. That is, even a golden age pathway savings rate is insufficient to overcome the continual drag on the economy arising from natural resource exhaustion. While such a decline in consumption may be greeted by some as advantageous for sustainability, in light of discussion in the previous section it can also be seen as acting against the interests of poverty elimination, and against the spirit of Phelps' Golden Rule.

Clearly, the exhaustible nature of primary resources needed for production on a finite planet creates serious difficulties for future generations in the neoclassical framework, just as the ecological economics

Fig. 1. Dynamic evolution of capital in place and unemployment from a state of under-capitalization and under-employment of labor.

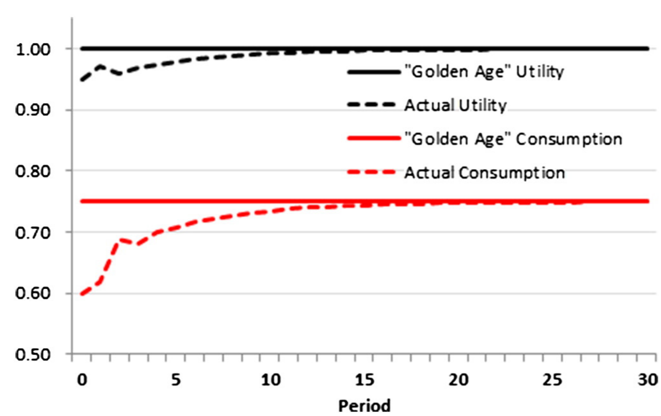

Fig. 2. Dynamic evolution of utility and consumption from a state of under-capitalization and under-employment of labor.

Table 4
Effects of a raw resource availability decline.

	Decline in utility per period	Decline in consumption per period
With resource technology declines	−0.12%	−0.30%
With no technology changes	0.00%	0.00%

tradition postulates. To the extent resource (and most plainly challenging today, energy) inputs can be provided by clean, abundant, and renewable means, the difficulties can be mitigated. And recycling of primary non-energy inputs can mitigate the economic drag of their decline, though thermodynamic limits promise to make this challenge ever-harder.

6. Sustainable Consumption Explorations — Considering Technology Improvements

Thus far the development has ignored the role of technology improvements, a feature of neoclassical economics that after all was central to the contribution of Robert Solow decades ago. A natural question is what might be the implications for a world of sustainable consumption when such are considered.

The story is best told by first ignoring growth in the labor force and exhaustibility of primary resources. Suppose we have an economy identical to that described previously but that now we permit technology gains in the intermediate goods and services sector *X*. Again, the assumption is that the available labor force $\overline{L}$ is unchanging and that the household utility function is fixed (preferences are unchanged). Specifically, suppose that technology gains in this sector derive from labor productivity gains alone, with $\lambda_{L_X} = 0.4\%$.

In such a case, the disturbing neoclassical consequence is that consumption must increase over time, even with no growth in the labor force. Economic variables evolve as shown below (Table 5):

Table 5
Effects of a labor technology improvement.

	Zero technology gains		With labor technology gains	
	Value in period 100	Growth rate	Value in period 100	Growth rate
u	1.00	0.00%	1.17	0.16%
C	0.75	0.00%	1.11	0.40%
S	0.25	0.00%	0.37	0.40%
l	2.00	0.00%	2.00	0.00%
Y	1.00	0.00%	1.48	0.40%
K	1.00	0.00%	1.45	0.40%
L	1.00	0.00%	1.00	0.00%
R	0.18	0.00%	0.26	0.40%
c	1.00	0.00%	0.74	−0.30%
w	0.75	0.00%	0.82	0.10%
r	0.25	0.00%	0.19	−0.30%

It is also seen in Table 5 that not only does consumption increase with labor productivity improvements, but so does the use of raw resources, *R*, to enable it. Both increases present challenges for the notion of sustainable consumption. Here we see an apparent disconnect with Daly's view that technology gains can deliver increases in economic value added even while resource use remains fixed (Daly, 2005, 2008), a topic we return to in the following sub-section.

Consumption increases because, while labor employment is unchanged, real wages ($^{w}/_{c}$) go up and real capital returns ($^{r}/_{c}$) stay fixed, thus expanding real household budgets. Budgets expand sufficiently to increase both consumption and savings, but leisure time is left unchanged.

Much of this dynamic arises from the decline in the price of output of goods and services. This decline in *c* is enabled by the increase in real final output *Y* despite fixed labor input, which duality theory says must be accompanied by declining *c*. Households can purchase more abundantly available goods and services at a lower cost. [10]

An obvious ancillary question is whether such technology gains can offset the welfare declines due to raw resource limitations noted in the preceding section. The answer to this question is yes, provided the technology gains and losses happen to offset each other in a very precise manner, reminiscent of the "knife-edge" solutions found in growth theory preceding Solow's breakthrough.

[10] Note that this reflects the spirit of Ohti's Theorem (Ohti, 1975) in that increases in real output must be accompanied by decreases in output cost for duality conditions to be honored. As Ohti proved, $\frac{1}{Y}\frac{\partial Y}{\partial t} = -\frac{1}{c}\frac{\partial c}{\partial t}$. While explanatory, this is a short-term, partial derivative, condition; here, we see that while output and cost trends indeed differ in sign, $\frac{1}{Y}\frac{dY}{dt} \neq -\frac{1}{c}\frac{dc}{dt}$ as the full derivative condition is more complex than addressed by Ohti's Theorem.

6.1. Sustainable Consumption Given Production Technology Gains

Now comes a central question — is a fixed-consumption golden age growth path achievable in the presence of production technology gains?

The answer to this question is hinted at in Table 1. If the true preferences of households depicted in the preceding section are characterized by utility function parameters ν and γ that adjust in just such a way as to offset the effects of a production technology gain, such a condition is possible.

A question this raises is what would cause such a preference mechanism to obtain? A possible foundation for such an expectation is the notion that households might at some point achieve a level of consumption that is "satisficing," that is, a consumption level beyond which additional consumption delivers them little or no utility. Evidence for such behavior is often claimed to be found in the household consumption patterns of the Scandinavian economies, where households are commonly said to sacrifice added earnings, and associated consumption, in favor of increased leisure time.

Suppose households have by one means or another achieved such a "satisficing" level of consumption. Might not the economy's productivity increases be captured by them in some other way, perhaps by increasing their leisure time allocation?

More rigorously, suppose that the utility function Eq. (8), instead of being static, is instead dynamic. A dynamic depiction of utility enables comprehension of consumption satiation. Specifically, suppose that function Eq. (8) takes the following form:

$$u_t(C_t, S_t, l_t) = aC_t^{\gamma_t} S_t^{\nu_t} l_t^{1-\gamma_t-\nu_t} \tag{11}$$

where the exponents of C_t, S_t, and l_t are time-dependent. This enables a depiction of utility wherein the contribution of *C* to households' utility is maximized at some level $C_t = \overline{C}_{satisficing}$, where $\overline{C}_{satisficing}$ is fixed for all time, even in a growing economy.[11]

The simulation model elucidates this. If we assume, as before, that $\lambda_{L_X} = \lambda_{L_R} = 0.4\%$ and all other technology gains are zero, but append to this the assumptions that γ and ν decline over time at 0.3%/period, we see the following result (Table 6):

In this world, physical consumption remains fixed and raw resource use is declining over time, a state of affairs such as ecological and sustainability economists like to dream of. It also reflects more closely the picture envisioned by Daly. Furthermore, households experience an increase in leisure time availability. The allocation of household activity looks as shown in Fig. 3.

[11] Note that this formulation does not necessarily depict changing preferences: households may have a strong, unchanging, preference for consumption remaining at some fixed level once achieved.

Table 6
Effects of a labor technology improvement with "satisficing" consumption.

	Zero technology gains		With labor technology gains and "satisficing" consumption	
	Value in period 100	Growth rate	Value in period 100	Growth rate
u	1.00	0.00%	1.26	0.21%
C	0.75	0.00%	0.75	0.00%
S	0.25	0.00%	0.25	0.00%
/	2.00	0.00%	2.29	0.11%
Y	1.00	0.00%	1.00	0.00%
K	1.00	0.00%	1.00	0.00%
L	1.00	0.00%	0.71	−0.35%
R	0.18	0.00%	0.16	−0.11%
c	1.00	0.00%	0.77	−0.26%
w	0.75	0.00%	0.82	0.09%
r	0.25	0.00%	0.19	−0.26%

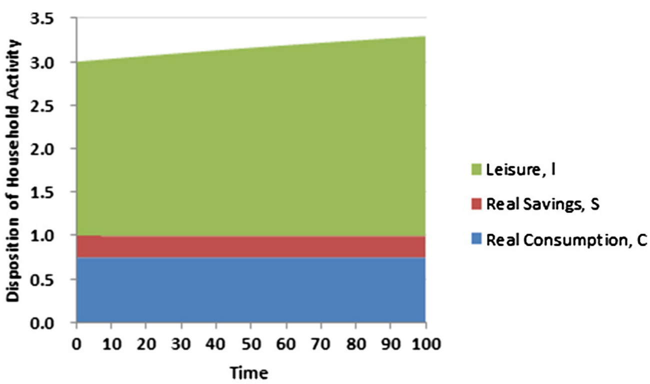

Fig. 3. Households take the benefits of technology gains in the form of increased leisure time.

The ongoing production technology gain enables households to increase leisure time at the rate of 0.11% per period. This is in part because real earnings from wages remain fixed in real terms.[12]

As is also evident, marginal returns to capital remain fixed in real terms, as the nominal capital returns decline at precisely the same rate as output price, namely 0.26% per period while household capital assets remain fixed. These results illustrate the importance of fully incorporating duality considerations in analyses like this.

The upshot of all this analysis is that there is nothing fundamental in neoclassical economics saying economic utility cannot grow indefinitely even in face of a requirement for a fixed consumption level. If technology gains persist indefinitely, consumption can stabilize and leisure time can increase asymptotically toward the maximum time available from the workforce. In this way, neoclassical economics gives us rigorous insights about the nature of, and potential for, a world of sustainable consumption.

6.2. Resource Efficiency Rebound

More efficient use of resources is a widely-prescribed pathway to sustainable consumption. If the goods and services consumed by households are produced with fewer resources, the argument goes, this will reduce the impact on the environment associated with their exploitation. This is a beguiling, seductive argument as it appears to offer a means to preserve consumption levels while not incurring significant societal costs beyond the costs associated with developing the needed efficiency technology. All that is required is clever innovation, presumably available in abundance. Present-day policy makers are enamored with this idea because it appears to be a clear win–win for all, devoid of controversial tradeoffs.

But the reality is not quite so simple, and the present framework illustrates why. Turning attention to the parameter τ_R in Eq. (9), which reflects the ability of sector X to improve the efficiency of its use of resources R, a natural experiment is to examine how R responds to changes in τ_R over time.

To keep the experiment pure, the following analysis assumes no labor or capital technology gains in either intermediates production or resource extraction, beyond the improved ability of the intermediates sector to use resources more efficiently. And, as before, the labor force is assumed fixed. Along with these assumptions, τ_R is assumed to grow at 1.0%/period so that $\lambda_R = 0.01$. Interpreting the results first requires a definition, drawn from the literature on "energy efficiency rebound"[13]:

$$\text{Rebound} = 1 - \frac{\text{Actual Resource Savings}}{\text{Expected Resource Savings}} \tag{12}$$

Expected Resource Savings has come to mean those savings one would expect were the efficiency gains to "take" on a one-for-one basis (as indicated by engineering calculations of efficiency improvements). This reflects the mental model adopted by many policy makers, and not a few economists, but which implicitly assumes production is characterized by a Leontief fixed-factors model (Saunders, 2008). According to this relationship (Eq. (12)), if actual resource savings equals the savings expected in a Leontief framework, rebound will be zero; if actual resource savings are zero, rebound will be 100%; if actual resource savings are negative (i.e., if the efficiency gain actually increases resource use), the efficiency gain is said to induce a "backfire" condition. The more flexible production function adopted here (i.e., decidedly not a Leontief function) combined with the empirical measurements for Sweden from Stern and Kander (2012) reveals the following results:

$$\text{Rebound} = 1 - \frac{\text{Actual Resource Savings}}{\text{Expected Resource Savings}} = 1 - \frac{0.035}{0.101} = 68\%. \tag{13}$$

That is, resource efficiency gains reduce the level of resource use over 100 periods not by 10.1%, as one might naively expect, but only by 3.5%. In the parlance of rebound economists, resource use "rebounds" by 68%.[14] The primary cause of resource rebound is the fact that greater efficiency in resource use both reduces its effective price and expands the production possibilities frontier for producers (and in parallel increases the disposable income of consumers).

As shown elsewhere,[15] the magnitude of rebound is heavily dependent on the degree of flexibility of the economy to adapt to the efficiency gain. On the production side, this flexibility is here embodied in the elasticity of substitution — the ease with which producers can substitute between the capital/labor combination of intermediates production and

[12] See online Appendix B for a mathematical elucidation of this.

[13] For energy, a large and burgeoning literature going back to Jevons (1865) and pioneered in the modern era by Brookes (1979, 1990a,b,c, 1992, 2000, 2004) and Khazzoom (1980, 1987, 1989) examines the rebound effect. Saunders (1992) established the first formal neoclassical theoretical foundation. More recent contributions come from Greene (1992), Howarth (1997), Greening et al. (2000), Saunders (2000a,b, 2005, 2008, 2013a,b, 2014 - in press), Schipper (2000), Schipper and Grubb (2000), Berkhout et al. (2000), Laitner (2000), Roy (2000), Binswanger (2001), Frondel (2004), Grepperud and Rasmussen (2004), Alcott (2005), Sorrell (2007, 2009), Hanley et al. (2009), Allen et al. (2006), Barker and Foxon (2006), Ayres and Warr (2009), Wei (2006, 2010), Turner (2009, 2014a,b), Herring and Sorrell (2009), Tsao et al. (2010), Jenkins et al. (2011), Druckman et al. (2011), Owen (2011), Fouquet (2012), Fouquet and Pearson (2012). (This listing is by no means comprehensive as this field is exploding, with new contributions appearing monthly.)

[14] Robert Solow long ago at least implicitly recognized the underlying mechanism: "while it's hard to break the habit, 'factor-augmenting' does not mean 'factor-saving.'" (Personal communication, 1991).

[15] Saunders (1992, 2008).

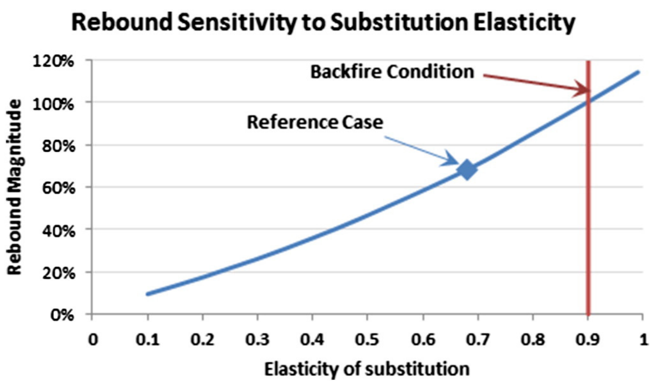

Fig. 4. Sensitivity of resource rebound to producers' substitution flexibility.

the resource input.[16] Accordingly, it is useful to examine the sensitivity of this rebound condition to this elasticity parameter (Fig. 4).

As seen, the greater the elasticity of substitution σ, the greater is the resource rebound effect. In fact, if this elasticity exceeds 0.9, we observe a "backfire" effect (rebound > 100%) — increased efficiency in the use of resources causes an outright increase in resource use. This is reminiscent of standard rebound theory found in the energy economics literature. There, with a CES-style production function, rebound is characterized by the following relationship[17]:

$$\text{Rebound} = \frac{\sigma}{1-s_E} \tag{14}$$

where s_E is the energy value share, σ is the energy substitution elasticity, and rebound is seen to increase with σ and can exceed unity (100%). Further, it was seen in Section 6 that technology gains in the intermediates sector increase resource use, so if a particular resource efficiency technology is accompanied by technology gains for the other intermediates inputs K_X and L_X (as is often argued to occur), resource efficiency rebound will be greatly augmented. Even more worrisome, if technology gains occur within the resources sector they will necessarily lead to a "backfire" condition.[18]

Note that these results apply to raw resources as a whole, whereas the rebound literature to date has focused virtually exclusively on energy.

The consequence is that resource use efficiency gains are not guaranteed to reduce resource use.

7. Sustainable Consumption — The Eight "Golden" Propositions

This at last leads us to our goal — describing these results in terms of propositions that marry neoclassical economics to the notion of sustainable consumption. They are "propositions" because they have not been proved analytically from first principles, but rather strongly suggest themselves when the theory is implemented with specific functional forms — in particular, a Cobb–Douglas utility function and a CES (Solow)-type production function.

Proposition 1. *In a world of non-growing population and no technology improvement in production, economic consumption, savings, and leisure time automatically evolve toward a stable state where they remain fixed indefinitely thereafter. Producers receive the capital and labor required to sustain this state. Accordingly, perpetual growth is not a requirement of the theory. Further, this is a condition that maximizes utility for all generations and so can be thought of as a (slightly more general) restatement of Phelps' Golden Rule of Accumulation.*

Proposition 2. *If this world is one in which production technology characteristics are of precisely the right kind to match consumer preferences, the three specific conditions of the classic Phelps' Golden Rule are met explicitly, and the utility maximizing condition is the same as Phelps' consumption-maximizing Golden Rule.*

Proposition 3. *The stable consumption magnitude that results will depend on household preferences (the characteristics of the household utility function). Depending on preferences among consumption, saving, and leisure time, this consumption level may be lower or higher, but still utility-maximizing for the household.*

Proposition 4. *Economies suffering from undercapitalization with respect to the available labor population will naturally move toward this golden age situation, provided the standard assumptions of neoclassical economics hold true. For a fixed population size, consumption in particular will approach the utility-maximizing golden age path of a fully capitalized economy and will stay at a fixed level thereafter.*

Proposition 5. *If the assumption of no production technology improvement is relaxed, a fixed level of consumption is attainable only if household utility preferences depend on consumption level. However, a stable consumption path is attainable nonetheless if true preferences in fact embody a "satiation" level that reflects a limited fixed consumption level. Moreover, in such case, productivity increases enable an expansion of leisure time, and household utility steadily increases. While this pathway is quite plainly utility-maximizing given these preferences, it represents a departure from the stricter classical statement of Phelps' Golden Rule where consumption is maximized.*

Proposition 6. *If raw resources are limited, or their externality burden is seen to be too high to enable a fixed, sustainable level of consumption for all time, household utility and consumption will decline while leisure time will increase not at all. The classical Phelps rule cannot be achieved with declining resource availability unless goods and services production technology continues to improve sufficiently to offset the resource loss.*

Proposition 7. *Improvements in the efficiency of resource extraction (improvements in capital and labor effectiveness in producing physical quantities of usable resource) cause an outright increase in the use of physical resources, a condition known as "backfire" in the energy economics literature. Such improvements increase resource use because they increase value-added output and income and, correspondingly, increase levels of both consumption and savings.*

Proposition 8. *If instead the efficiency improvement comes in the form of enabling the production of goods and services using less physical resource, the use of raw resources declines, but not in a one-for-one manner with the technical efficiency gain. With sufficiently great flexibility in the production process (greater ease of substitution between the physical resource and the capital/labor used in the production of intermediate and final output), a backfire condition is still possible. Even if not, use of raw resources will not decline in a one-for-one manner with the magnitude of the efficiency improvement, a condition known as "rebound" in the energy economics literature.*

8. Cautions and Limitations

Despite the alleged strengths of this approach, serious researchers need a clear delineation of the limitations implied in both the theoretical framework and the simulation here implementing it. First attention goes to the theoretical framework, which is limited in several ways:

[16] As shown in Saunders (2008), the degree of energy efficiency rebound depends upon multiple factor own- and cross-substitution elasticities in the case of the more general Translog function.

[17] Saunders (2008).

[18] See online Appendix D for further elucidation of this effect.

- There is no explicit consideration of the stock limits to "natural capital," except inasmuch as raw resources are treatable as exhaustible and/or ever-more-costly to exploit without inducing environmental damage;
- Accordingly, the framework is silent on what magnitude of consumption will be, in fact, sustainable;
- It assumes markets are efficient in maximizing welfare in the aggregate (a huge literature underpinned by the work of Joseph Stiglitz (1976, 1979) challenges this assumption);
- Income distribution issues are not addressed in this framework, thus setting aside a potentially major concern related to the social stability no doubt required to assure long-run "sustainable consumption";
- It assumes perfectly competitive markets; in today's world, oil producing countries engage in oligopolistic behavior, meaning resource supply is decidedly non-competitive.
- The framework assumes a single output of the economy, Y, that carries a single price, c;
- It assumes a closed economy, with no imports or exports;
- It assumes a single intermediate good produced using a single raw resource input:
  - Intermediate inputs are not distinguished by firm or sector, as would be the case for an input–output framework;
  - The resource sector does not distinguish among raw materials, including particularly distinguishing energy from other primary resources.
- It assumes an aggregate utility function across households;
- There is no government sector, and no taxes paid;

  The framework relies on standard microeconomic assumptions that can be interpreted as limiting:
  - Production is defined according to a function that is continuous, differentiable, and satisfies diminishing returns to the variable factor: $\frac{\partial f(x_1,x_2,\ldots,x_n)}{\partial x_i}<0$;
  - Production is constant returns to scale (CRS);
  - Consumer demand is derivable from a utility function that is likewise continuous, differentiable, homogeneous and of constant returns to scale.
- Capital is not vintaged. The assumption is that the production function somehow comprehends all capital in place, treating all capital as having some common, or at least "average," technology, whether newly added or old. In reality, agents installing new vintages of capital face a different production possibilities frontier from their forebears. A "putty-clay" formulation would produce more convincing results.

The numerical implementation reported here makes two additional, rather consequential, assumptions:

- The production function is of a CES (Solow) form;
- The utility function is of a Cobb–Douglas form.

While the framework itself in principle accommodates more general functional forms, the simulation results reported here must be cautiously interpreted as resting on these two, quite restrictive, assumptions. In particular, as described elsewhere (Saunders, 2008), more flexible functional forms can deliver quite different resource consumption results from those relying on functional forms such as employed here.

9. The Debate Re-Cast

This neoclassical framework enables a re-casting of the Solow–Stiglitz–Daly debate cited at the outset. While developed solely in the language and mathematics of neoclassical economists, the framework provides substantial confirmation of some ideas born in the ecological economics community, even while it challenges others.

On the confirmatory side, the results herein indicate that economic welfare, in the form of increased household utility, can increase indefinitely as technology advances even while economic output stays fixed and resource use declines, provided only that households attain some "satisficing" level of physical consumption. This is because households can take the benefits of future technology gains in the form of increased leisure time, continually increasing their utility. This result was foreseen long ago by Herman Daly.

Further, while Daly has expressed concern that full employment may not be possible in such a world (Daly, 2005), in fact such an economy realizes full employment in the sense that households provide labor to producers in precisely the amount they wish, and producers use this labor productively to serve household needs. Another concern raised by Daly, namely that lack of growth "would most likely cause interest rates to fall" (Daly, 2005), is not borne out by the framework. Instead, returns to capital stay fixed in real terms (and it is real returns that matter to producers and investors). So criticisms of ecological economics based on these concerns raised by Daly himself are unfounded, at least in a neoclassical world.

Moreover, the notion of natural capital and its limitations receives confirmation inasmuch as "golden age pathways," whether in the Phelps sense of maximizing future consumption or in the sense of maximizing the utility of future generations, are not neoclassically possible with depleting natural resources — even leaving externalities aside. This natural capital limitation on "golden age pathways" holds true despite the much more aggressive substitution possibilities between natural and human-derived inputs contemplated in the simulation model, compared to what many ecological economists argue to be the case. It is true however, that production technology gains of a very precise nature could offset these losses (again with externalities set aside).

Confirmatory also are the results indicating that both stocks and flows of "natural capital" will be determinative of future sustainability, just as ecological economists have forcefully asserted, and that account must be taken of the deeply problematic nature of limitations arising from both of these as regards practically realizing a sustainable global economy capable of being maintained into the indefinite future. Also, human-manufactured capital is shown to be complementary to natural capital, but substitutable for natural capital in a different way.

On the challenging side, the oft-heard criticism that neoclassical economics is reliant on an assumption of continual growth is shown to be false. The results demonstrate that growth is not required for a competitive private ownership economy to flourish. Even without technology gains, a fixed-for-all-time level of economic activity and consumption is the natural consequence for a neoclassical economy with no growth in the labor force. In such an economy (and even one with technology gains), producers maximize profits and households maximize utility; households provide all the capital and labor needed for production to be sustained at a fixed level indefinitely; and labor is fully employed in the sense that households trade off labor supplied and leisure time exactly according to their preferences. "Growth for growth's sake" may be an integral part of many mindsets in today's political economy, but it is not an integral part of neoclassical economics.

A further challenge comes in the form of the physical consumption consequence of poverty elimination. Ethical considerations aside, neoclassical forces are shown to drive increasing consumption in under-capitalized and under-employed economies, at least until "golden age" pathways are realized and consumption realizes a "satisficing" level.

Finally, there is the popularly-held view that improved efficiency in using natural resources is a near panacea for sustainable consumption. Many, but not all, ecological and sustainability economists have fallen into this trap, a notable exception being Ayres (e.g., Ayres and Warr, 2009). Instead, this framework demonstrates that efficiency gains in the use of resources carries with it a "rebound" effect that can greatly reduce, or even reverse, the consequent savings of natural resources. The "decoupling" of natural resource use from economic activity professed by many to be upon us is not much in evidence in a world where substitution possibilities prevail in any substantive way.

10. Conclusion

The apologia for neoclassical economics herein offered seeks to counter frequently-espoused proclamations that the theory is fundamentally at odds with the possibility that Earth's peoples can eventually realize sustainable consumption levels without abandoning private ownership of means of production, individual utility-maximizing behavior, producer profit-maximizing behavior, and the notion of competitive equilibrium.

Because of the care with which generations of brilliant economic minds have assembled it, neoclassical economics points a very reliable finger, usually, at powerful economic forces at work. Ecological and sustainability economists would do well to exploit its capability to generate important insights that bear on the question of sustainability.

It is dearly to be hoped that the thoughts and methodology offered here will soon be superseded by the work of others who will establish a more complete foundation for a neoclassical theory of sustainable consumption.

10.1. A Note on the Simulation Model

The simulation model used to develop the quantitative results reported here is freely available, is open-source, and is posted alongside this article. The model is user-friendly, includes a user guide, and allows users to explore the effects of changing various parameter assumptions to, it is hoped, further advance learning and insight.

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I would like to thank two anonymous referees whose comments greatly improved the quality of this paper. Also, it should be evident to any reader that a primary motivation for the present paper arises from the enormous influence of Herman Daly on the thinking of economists who care about sustainability.

Additionally, I wish to take the unusual step of acknowledging those whose work has in factual reality provided the sine qua non of this article, work all too frequently taken for granted. Robert Solow established modern neoclassical growth theory and the central role of technology in growth. Gerard Debreu and Kenneth Arrow demonstrated the profound validity of general equilibrium in a competitive private ownership economy. Edmund Phelps formally described the connection between consumption/savings choices and intergenerational equity and discovered Golden Rule behavior. Ronald Shephard showed how prices and quantities must be locked together in an equilibrium economy and why both must be considered simultaneously. Franco Modigliani and his colleagues established the modern theory of consumption. Each of these accomplishments was hard-won and each represents a truly fundamental advance in our economic understanding. It would be a great misfortune for ecological economists to overlook the lasting power of these monumental contributions — and in particular their power to inform our deeper understanding of long-term global sustainability.

Supplementary data: technical appendices and simulation model

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ecolecon.2014.06.011.

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