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Earth System Dynamics Discussions

Interactive comment on "No way out? The double-bind in seeking global prosperity along with mitigated climate change" *by* T. J. Garrett

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In order to clarify the economics in this paper, particularly in response to the questions raised in the constructive comments, the following items have been changed.

1. Abstract. The abstract has been slightly modified for clarity and to tone down the wording.

2. To aid clarity on the link between the economic representation of civilization proposed here and the thermodynamic representation, Figure 1 and its caption have been modified to more clearly illustrate the analog between the two representations. The text has been modfied to be consistent with the Figure. Specifically, for clarity, it is now expressed more consistently throughout (rather than just in

a footnote) that the total potential driving flows is $\Delta G = \breve{n}\Delta\mu$, so that interface growth at constant potential is most explicitly the time derivative of the material quantity $\breve{n}$. The advantage of making this more clear is that it makes it more evident that civilization is composed of matter, that it is this matter that drives flows, and that real economic production is a production of matter that is orthogonal to consumption. The point here is to create a stronger distinction between standard economic models where consumption is subtracted from production, and this thermodynamic formulation where the two quantities are orthogonal and therefore cannot be differenced.

3. The following sentence was added to clarify the fundamental relationship $a = \lambda C$.

   If there is no energy consumption, then civilization is worthless because the activities that sustain civilization's value cannot be maintained. Effectively civilization becomes indistinguishable from its surroundings.

4. To clarify the definition of wealth here a statement is added

   Equivalently, economic production is a consequence of a convergence of the material and energetic flows associated with wealth

$$\frac{dC}{dt} \equiv P$$

5. In response to comments from Reviewers 1, 2 and 3, the following paragraph has been added to clarify the difference with traditional models:

   Wealth *C* is analogous to the term "capital" used in traditional economic growth frameworks in the sense that it has units of currency, rather than currency per unit time. However, it is much more general. Traditional economic models separate capital from labor as distinct motive forces of economic production (Solow, 1956), sometimes including supplies of energy

and raw materials in an appeal to thermodynamic constraints (Saunders, 2000; Warr and Ayres, 2006). Labor, capital and physical inputs are all set to exponents that are tuned to provide agreement with observed sectoral or national production statistics. Capital grows only due to "investments" that are separated from household and government "consumption". Household consumption never adds to capital. For one, people are not normally considered to be part of capital. For another, value that is consumed is presumed to be gone forever.

Here, the economic approach is quite different. As shown in Fig. 1, civilization is defined as a whole such that no distinction is made between the human and non-human elements of the global economic system. Economic elements are not independent. Rather, all economic elements in civilization form a generalized capital that works in concert to enable the "downhill" flows of material in a field of potential energy. Effectively, civilization is assumed to be homogeneous and "well-mixed". Strictly, this assumption requires only that the speed of financial interactions between all civilization elements is rapid compared to the timescales of global economic growth (for a full discussion see Appendix B in (Garrett, 2011)).

The second major difference is that consumption is thermodynamically orthogonal to production. Traditional economic models subtract consumption from production to obtain an investment in the value of capital. In Figure 1, by contrast, consumption is equivalent to the global scale flow of primary energy resources through civilization. This consumptive flow of matter and potential energy is downhill from high to low potential, and it is at right angles to the constant potential surface along which civilization lies. Economic production is proportional to the expansion of this potential surface. Thus, consumption and production cannot be differenced because the two quantities are mathematically orthogonal. Consumption is

not a component of production, but rather production is the *convergence* in thermodynamic consumption. Only if civilization consumes more energy than it dissipates can net work be done and economic value be produced.

Thus, unlike traditional models, there is no need for any tuning of exponents in a production function because labor is subsumed into capital, and capital is fundamentally assumed to be an implicit representation of energy consumption. While this perspective may be highly unorthodox, the absence of tuning means that the physical approach does in fact rest on a testable, falsifiable hypothesis, which is that the ratio of current energy consumption to accumulated, inflation-adjusted production λ is a constant.

6. While Reviewer 3 didn't explicitly request this comparison, he did request a broader link to pior work in the area of energy economics. It turns out a robust link can be drawn to the Energy Returned on Energy Invested (EROI) concept that is becoming increasingly popular (Murphy and Hall, 2010). Discussion of this link is now provided in Section 3.2. It turns out that the thermodynamic calculation of the inflationary pressure is simply the inverse of the EROI value.

7. Also in response to Reviewer 3. Figure 1 has been redrafted and the text has been re-arranged to highlight more explicitly that production P is tied to thermodynamic work w or the divergence of flows da/dt. In particular, in response to the suggestion that a direct comparison be made between P and da/dt, the following paragraph was added

   A theoretically equivalent approach to calculating λ is to take the respective derivatives of a and C in order to compare the inter-annual change in energy consumption da/dt to the real GWP P. Derivatives of measured quantities are always more noisy than their integrals. For example, the magnitude of da/dt is only about a couple of percent per year, where a itself is sub-

ject to measurement uncertainties that, while unpublished, are plausibly of a similar magnitude. Nonetheless, the calculated value for $P/(da/dt)$ of 11.6±4.1 milliwatts per 1990 US dollar is statistically consistent with the derived value for $\lambda = C/a$ of 9.7±0.3 milliwatts per 1990 US dollar.

8. Reviewer 3 lamented an incomplete effort to relate the physical concept of thermodynamic potential with capital. This concept is actually at the core of this study, and is now clarified where the text now reads

   Taking λ to be a constant, it follows from Eqs. 1, 3, and 5, that wealth C, rates of potential energy consumption a, and the size of the interface representing the potential gradient that drives flows $\Delta G = \breve{n}\Delta\mu$ are all proportional. In this case the rate of return η for economic growth applies equally to each

9. In response to criticisms that inflation is a purely monetary phenomenon, and therefore unrelated to climate change, the text has been modified to read as follows

   While a wide variety of theoretical economic explanations have been presented for what drives inflation, none have been solidly rejected, and the field remains highly fluid (Parkin, 2008). Price inflation is traditionally viewed as a simple imbalance between the monetary supply and economic output, and therefore mostly a matter for central bank control. What this perspective does not address is why inflation appears to have such deleterious impacts on real economic growth (Sarel, 1996), or what external forces drive the initial imbalance. As has been noted by the current head of the US treasury, central banks respond to inflationary pressures that might arise from external shocks to primary energy supplies, notably oil (Bernanke et al., 1997). More recently, it has been pointed out how it is likely that climate change is currently driving up food prices through its

   adverse effects on crop production (Lobell et al., 2011)

   A full thermodynamic account of the effects of climate change on the prices of individual goods would require a model that explicitly resolves both banks and the goods themselves. This is beyond the scope of the treatment here in which civilization is treated purely as a whole. But while no direct account can be made here of the role of banks in changes to the monetary supply, what can be done is to provide a thermodynamic formulation for how adverse climatic conditions might lead to inflationary pressures that would have to be addressed by central banks (Bernanke et al., 1997) . In fact, banks and externally imposed natural disasters can both play a role in the real devaluation of existing wealth. Natural disasters destroy life and property, reducing the amount of real value that has previously been produced. Similarly, the real value of previously printed money declines if banks are excessively loose with the monetary supply. In either case, inflation tends to follow because of a fall in the real value of the past accumulation of wealth.

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1. *For example some IAMs do represent physical flows.*

   The text has been rewritten to read: **Modern IAMs are based on neo-classical economic models that, unlike EaSMs, do not explicitly represent physical flows as a material flux down gradients in potential energy.**

2. *it is unclear who are the subjects in statements such as “what we normally term”, what precisely is meant by an “economic signal that can be meaningfully distinguished from noise”, etc.*

   The two statements have been rewritten to read

Thus, what is normally termed as "economic growth"

and

Figures 2 and 3 show no clear trends in the decay coefficient γ that can easily be attributed to accelerating climate change. Up until this point, the dominant signature remains interannual variability in γ.

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