

## ***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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Received and published: 10 June 2011

I fully agree that a theoretical justification is needed to lend support to the empirical tests that are provided here. The theoretical justification in this article is outlined in Section 2, but more extensively in the prior article in Climatic Change, where it is stated that

"While a precise definition of civilization is arbitrary, civilization is most commonly quantified in purely fiscal terms. Thus, the goal here is to examine whether it is possible to link fiscal quantities to the more thermodynamic model defined above. To this end, an argument can be made that, if what physically distinguishes civilization from its environment is some thermodynamic potential  $\Delta G$  at constant temperature and pressure, civilization implicitly assigns inflation-adjusted (or real) monetary value to what  $\Delta G$  en-

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ables—the total rate of energy consumption  $a$ . To borrow a phrase, “money is power” because, if all current exothermic processes supporting civilization were to suddenly cease such that  $a$  equalled zero, all civilization would become worthless; it would no longer be associated with a non-equilibrium level of potential energy  $\Delta G = a/\alpha$ . Simply, there would be no definable material interface  $\tilde{n}$  between civilization and its environment.

As an example, the potential energy in oil combustion is valuable, but only to the extent it that it can interact with the interface separating civilization from its environment. It has zero value if it burns wastefully in the desert, and zero value in its unavailable chemical and nuclear bonds. From society’s perspective, any societal element, whether living or synthetic, only has value to the extent it is able to operate in synergy with all other elements to define an interface with environmental available energy. An unavailable road from nowhere to nowhere is just pavement on the ground. But the same road between two cities is part of a larger organism that works collectively at net rate  $w$  to grow access to the primary energy supplies that civilization requires.”

Note that the definition of work here is quite precise, in that it represents an expansion of civilization itself through stretching of the interface between civilization and primary energy supplies, as illustrated here in Figure 1. It is this stretching that leads to the global scale feed-backs that form the basis for the dynamic formulation presented here. Ayres and Warr have also discussed the importance of work in civilization growth, but their definition of work is different, focusing more narrowly on mechanical effort within civilization, rather than a more global (and necessarily abstract) stretching of civilization boundaries. Ayres and Warr separate human labor from machine labor, for example. Here, no distinction is made. We and our machines are all part of a global whole.

I appreciate the suggestion that the more intuitive argument for many would be to make the case that thermodynamic work and economic production are tied through a constant, such that  $\lambda = \alpha w/P$ . This wasn’t the way I initially approached the problem, but what is suggested is an equally valid approach to emphasizing instead the identity

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$$\lambda = a/C = a / \int_0^t P dt'$$

The slight problem here is that  $\alpha$  is unknown, other than being theoretically treated as a constant (effectively a physical diffusivity defining the gradient  $\Delta G$ ). On the other hand,  $P$  and  $a$  are actually known. Thus, it is only the expression  $\lambda = a/C = a / \int_0^t P dt'$  that can be tested directly.

As an alternative, I could show empirical evidence supporting the constancy of  $\lambda = da/dt/P$ . Indeed, in earlier drafts I did precisely this. The problem here is that  $da/dt$  is a much more noisy measurement than  $a$ . Derivatives are always more noisy. And, if it is shown to hold that  $\lambda = a / \int_0^t P dt'$ , mathematically, it has to hold that  $\lambda = da/dt/P$ . Regardless, I will emphasize that the two perspectives are mathematically equivalent in a revision.

Although I am not qualified to comment on this in depth, I am surprised that GDP is considered an empirically shaky metric. From the basis of the model presented here, it seems that it must be precisely the correct metric. Sure, GDP subsumes only a very small fraction of the total transactions and activities within society. But this critique of GDP is in fact fully consistent with the framework that is presented here. Here, GDP does not represent civilization economic activities, but rather only a quantification of the rate of growth of civilization activities.

As discussed previously in the comments, GDP and consumption are treated as orthogonal quantities. Our salaries are representations of the perceived contribution to the expansion of civilization. The rest of our non-work activities may sustain us, but we don't get paid for them, and they are not accounted for in GDP. We don't get paid to eat for a good reason. Our eating only serves to sustain civilization at its current size.

Of course, the reality is that the GDP and the rate of consumption are inseparable. If we don't eat, we can't work, and vice versa. Looking at Figure 1 in the article here, civilization activities (involving consumption) and expansion of civilization consumption (as measured by the GDP), lie along the same potential surface. Viewed from a global

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perspective, no distinction can be made between those internal circulations within the surface that stretch the surface, and those circulations that are already part of the surface.

There are many analogues in physics for this perspective. To describe the potential surface occupied by civilization, I used the word "well-mixed" in this article for a very specific reason. Direct parallels can immediately be drawn to, for example, a deepening atmospheric boundary layer, or a growing cloud droplet where the molecule circulations within the droplet are not explicitly resolved. It is these parallels that I am currently using to help guide the more detailed non-equilibrium thermodynamic development that Dr. Herrmann-Pillath previously recommended.

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Interactive comment on Earth Syst. Dynam. Discuss., 2, 315, 2011.

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