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IS GLOBAL COLLAPSE IMMINENT?

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Is Global Collapse Imminent? An Updated Comparison of *The Limits to Growth* with Historical Data

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Abstract

The Limits to Growth "standard run" (or business-as-usual, BAU) scenario produced about forty years ago aligns well with historical data that has been updated in this paper. The BAU scenario results in collapse of the global economy and environment (where standards of living fall at rates faster than they have historically risen due to disruption of normal economic functions), subsequently forcing population down. Although the modelled fall in population occurs after about 2030—with death rates rising from 2020 onward, reversing contemporary trends—the general onset of collapse first appears at about 2015 when per capita industrial output begins a sharp decline. Given this imminent timing, a further issue this paper raises is whether the current economic difficulties of the global financial crisis are potentially related to mechanisms of breakdown in the *Limits to Growth* BAU scenario. In particular, contemporary peak oil issues and analysis of net energy, or energy return on (energy) invested, support the *Limits to Growth* modelling of resource constraints underlying the collapse.

Checking on the Limits to Growth

With over forty years of hindsight available since *The Limits to Growth (LTG)* was first published (Meadows et al., 1972, Meadows et al., 1974), it is timely to review how society is tracking relative to their ground-breaking modelling of scenarios, and to consider whether the global economy and population is on a path of sustainability or collapse. Over a similar timeframe, international efforts based around a series of United Nations (UN) conferences have yielded mixed results at best (Linner and Selin, 2013, Meadowcroft, 2013). In addition to unresolved critical environmental issues and resource constraints such as anthropogenic climate change and peak oil, the global economy is also beset by ongoing challenges from the Global Financial Crisis (GFC), not least of which are lingering levels of extraordinary debt. The standard political remedy of growing the economy out of debt has potential ramifications for environmental stability, with evident negative feedbacks on the economy. The intertwined economy-environment dependencies embodied in the original 1970's *LTG* modelling provide an opportunity to examine how the global predicament has unfolded and what it might mean for the future.

Through a dozen scenarios simulated in a global model (World3) of the environment and economy, Meadows et al. (1972, p. 125) identified that "overshoot and collapse" was avoidable only if considerable change in social behaviour and technological progress was made early in advance of environmental or resource issues. When this was not achieved in the simulated scenarios, collapse of the economy and human population (ie. a relatively rapid fall) occurred in the 21st century, reducing living conditions to levels akin to the early 20th century according to the modelled average global conditions. Exactly how this would play out in the real world is open to conjecture, as noted below.

Despite the *LTG* initially becoming a best-selling publication, the work was subsequently largely relegated to the "dustbin of history" by a variety of critics (eg., Lomborg and Rubin, 2002). These critics perpetuated the public myth that the *LTG* had been wrong, saying that it had forecast collapse to have occurred well before year 2000 when the *LTG* had not done this at all. Ugo Bardi's *The Limits to Growth Revisited* (2011) comprehensively details the various efforts to discredit the *LTG* study. He draws parallels with documented campaigns against the science of climate change and tobacco health impacts. Three economists- Peter Passel, Marc Roberts, and Leonard Ross- initiated criticisms in a *New York Times* Sunday Book Review article in 1972. They made false statements (eg. "all the simulations based on the Meadows world model invariably end in collapse"), and also incorrectly claimed that the book predicted depletion of many resources by about 1990. The US economist William Nordhaus made technically erroneous judgements (in 1992) by focusing on isolated equations in World3 without considering the influence that occurs through the feedbacks in the rest of the model. In 1973 a critique of the *LTG*, edited by physicist Sam Cole and colleagues at the University of Sussex, contained a technical review of the World3 modelling and essays based on ideology that attacked the authors personally. According to Bardi, the technical review fails because it largely concerned how the World3 model could not be validated from the perspective of simple linear modelling, which is an inappropriate test for a non-linear model. The review also established that the model could not run backwards in time, though this is an unnecessary requirement for the model to run forward properly. Criticism of the study continued for about two decades, including other noted economists such as Julian Simon, along the vein of such misunderstandings and personal attacks. For the last decade of the twentieth century, however, criticism of the *LTG* centred on the myth that the 1972 work had predicted resource depletion and global collapse by the end of that century. Bardi identifies a 1989 article titled "Dr. Doom" by Ronald Bailey in *Forbes* magazine as the beginning of this view. Since then it has been promulgated widely, including through popular commentators such as the Danish statistical analyst Bjørn Lomborg, and even in educational texts, peer-reviewed literature, and reports by environmental organisations.

Over the last decade, however, there has been something of a revival in awareness and understanding of the *LTG*. Most recently, Randers (2012a)—a *LTG* co-author—has published his forecast of the global situation in 2052 and renewed the lessons from the original publication (Randers 2012b). A turning point in the debate occurred in 2000 with the energy analyst Simmons (2000) raising the possibility that the *LTG* modelling was more accurate than generally perceived. Others have made more comprehensive assessments of the model output (Hall and Day, 2009, Turner, 2008); indeed, my earlier work found that thirty years of historical data compared very well with the *LTG* "standard run" scenario. The standard run scenario embodies the business-as-usual (BAU) social and economic practices of the historical period of the model calibration (1900 to 1970), with the scenario modelled from 1970 onwards.

This paper presents an update on the prior data comparison by Turner (2008). An update is especially pertinent now because of questions raised about how the current economic downturn—commonly associated with the GFC—may relate to the onset of collapse in the *LTG* BAU scenario. Is it possible that aspects leading to the collapse in the *LTG* BAU scenario have contributed to the GFC-related economic downturn? Could it be that this downturn is therefore a harbinger of global collapse as modelled in the *LTG*?

To provide context and convey the importance of understanding global dynamics, this paper first summarises the mechanisms that play-out in the modelled BAU scenario. Subsequently, the modelled trajectory is compared with some forty-years of historical data (which are outlined in the appendix). The appendix also provides comparison of the data with two other scenarios, namely "comprehensive technology" and "stabilized world" scenarios (with full details in Turner, 2012)—showing that the comparison strongly favours the BAU scenario only. On the basis of this comparison, we discuss what the modelling might mean for a resource-constrained global economy. In particular, the paper examines the issue of peak oil and the link between energy return on investment (EROI) and the *LTG* World3 model. The findings lead to a discussion of the role of oil constraints in the GFC, and a consideration of the link between these constraints and general collapse depicted in the *LTG*. This paper does not attempt to deal with the critical but vexed issue of appropriate governance; other research is shedding light on the difficulties thwarting change (eg. Harich, 2010, Rickards et al., 2014). Instead, it aims to forewarn of potential global collapse—perhaps more imminent than generally recognised—in the hope that this may spur on change, or at least to prepare readers for a worst case outcome.

Modelling future worlds

The computer model called World3, developed for the *LTG* study, simulated numerous interactions within and among the key subsystems of the global economy: population, industrial capital, pollution, agricultural systems, and non-renewable resources. For its time, World3 was necessarily coarse, for example modelling the total global population rather than separate regions or nations. In the system dynamics approach, causal links were made mathematically to reflect the influence of one variable on another (not necessarily in a linear fashion), both within and between various sectors of the global economic system. In this way, positive and negative feedback loops were established, where the outcome in one part of the system subsequently returns by a chain of influences to affect itself. When positive and negative feedback loops are finely balanced, a steady state outcome results (or oscillations about an average); however, when one loop dominates, an unstable state is the result, such as the simple case of exponential growth when there is a dominant positive feedback. A classic example is the accelerating growth of a biological population, such as bacteria, in which the birth rate at one point in time is proportional to the size of the population at that time.

The effect and control of these feedbacks depends on the presence of delays in the signals from one part of the world system to another. For instance, the effects of increasing pollution levels on human life expectancy or agricultural production may not be recognised for some decades after the pollution is emitted. This is important because unless the effects are anticipated and preventive action taken in advance, the increasing levels of pollutants may grow to an extent that prohibits correction. These are the dynamics that lead to "overshoot and collapse".

The World3 model simulated a stock of non-renewable as well as renewable resources. The function of renewable resources in World3, such as agricultural land and the trees, could erode as a result of economic activity, but they could also recover their function if deliberate action was taken or harmful activity reduced. The rate of recovery relative to rates of degradation affects when thresholds or limits are exceeded as well as the magnitude of any potential collapse.

To explore "the broad behaviour modes of the population-capital system" (Meadows et al. 1972, 91) the *LTG* presented a dozen scenarios exploring the effects of various technological improvements and societal or policy changes. The scenario series started with a "standard run" which encapsulated business-as-usual (BAU) values in the model for the future. Parameter trends for this scenario were based on historical data and behaviour (established to reproduce approximately the growth and dynamics observed from 1900 to 1970).

Impending collapse of the BAU scenario

As described below, data from the forty years or so since the *LTG* study was completed indicates that the world is closely tracking the BAU scenario. In the BAU, during the 20th century increasing population and demand for material wealth drives more industrial output, which grows at a faster rate than population. Pollution from increasing economic activity increases, but from a very low level, and does not seriously impact the population or environment.

However, the increased industrial activity requires ever increasing resource inputs (albeit offset by improvements in efficiency), and resource extraction requires capital (machinery) which is produced by the industrial sector (which also produces consumption goods). Until the non-renewable resource base is reduced to about 50 per cent of the original or ultimate level, the World3 model assumed only a small fraction (5 per cent) of capital is allocated to the resource sector, simulating access to easily obtained or high quality resources, as well as improvements in discovery and extraction technology. However, as resources drop below the 50 per cent level in the early part of the simulated 21st century and become harder to extract and process, the capital needed begins to increase. For instance, at 30 per cent of the original resource base, the fraction of total capital that is allocated in the model to the resource sector reaches 50 per cent, and continues to increase as the resource base is further depleted (shown in Meadows et al., 1974).

With significant capital subsequently going into resource extraction, there is insufficient capital available to fully replace degrading capital within the industrial sector itself. Consequently, despite heightened industrial activity attempting to satisfy multiple demands from all sectors and the population, actual industrial output (per capita) begins to fall precipitously from about 2015, while pollution from the industrial activity continues to grow. The reduction of inputs to agriculture from industry, combined with pollution impacts on agricultural land, leads to a fall in agricultural yields and food produced per capita. Similarly, services (eg. health and education) are not maintained due to insufficient capital and inputs.

Diminishing per capita supply of services and food causes a rise in the death rate from about 2020 (and a somewhat lower rise in the birth rate, due to reduced birth control options). The global population therefore falls, at about half a billion per decade, starting at about 2030. Following the collapse, the output of the World3 model for the BAU (Figure 1) shows that average living standards for the aggregate population (material wealth, food and services per capita basically reflecting OECD-type conditions) resemble those of the early 20th century.

The implications of the BAU scenario are stark: Figure 1 depicts global collapse of the economic system and population. Essentially this collapse is caused by resource constraints (Meadows et al., 1972), following the dynamics and interactions described above. The calibrated dynamics reflect observed responses within the economy to changing levels of abundance or scarcity (Meadows et al., 1974), obviating the need for modelling prices as the communication channel of the economic responses.[i]

The *LTG* 'Business As Usual' scenario tracks reality

With forty years passing since the original *LTG* modelling, it is opportune to examine how well the scenarios reflect reality. In this section a graphical comparison is presented of the historical data with the BAU scenario described above (Figure 1). It is evident from Figure 1 that the data generally aligns strongly with the BAU scenario (for most of the variables); while the data does not align with the other two scenarios (Turner, 2012, Turner, 2008) (see Appendix 1).

The demographic variables displayed in Figure 1 continue to show the same comparisons as seen in the thirty year review (Turner, 2008), so that population would peak somewhat higher than the BAU by 2030, or later according to an extrapolation of the difference between the birth and death rates. It is more evident now, however, that the crude death rate has leveled off while the birth rate continues to fall, which are general trends seen in the three scenarios, albeit at different values. Notably, the death rate reverses its monotonic decline and begins to climb in all scenarios within a decade; significantly so in the standard run (and comprehensive technology) scenario by 2020.

Outputs of the economic system (Figure 1) show trends mostly commensurate with the *LTG* BAU. Importantly, any downturn in industrial activity due to the GFC has not been captured in the historic data since these were only available to 2007. Nevertheless, the observed industrial output per capita illustrates a slowing rate of growth that is consistent with the BAU reaching a peak. In this scenario, the industrial output per capita begins a substantial reversal and decline at about 2015. Observed food per capita is broadly in keeping with the *LTG* BAU, with food supply increasing only marginally faster than population. Literacy rates show a saturating growth trend, while electricity generation per capita (upper data curve) grows more rapidly and in better agreement with the *LTG* model (Figure 1).

Global pollution measured by CO2 concentration is most consistent with the BAU scenario (Figure 1), but this ten year data update indicates that it is rising at a somewhat slower rate than that modelled. This could be due to a number of factors, which cannot be separately identified in this analysis. For instance, in comparison with the BAU model output, lower observed industrial output per capita is consistent with lower observed pollution generation, though this effect will be offset by the slightly higher observed population levels. It is also possible that the dynamics of persistent pollution generation by different economic activities or assimilation in the environment are not parameterized in the World3 model precisely in terms of actual CO2 dynamics (which is still a topic of active research). In this possibility, the recent data are consistent with a slightly higher assimilation rate, or alternatively, a lower pollution generation rate in the agriculture sector compared with the industrial sector (since the relative rate of food production is greater than industrial output).

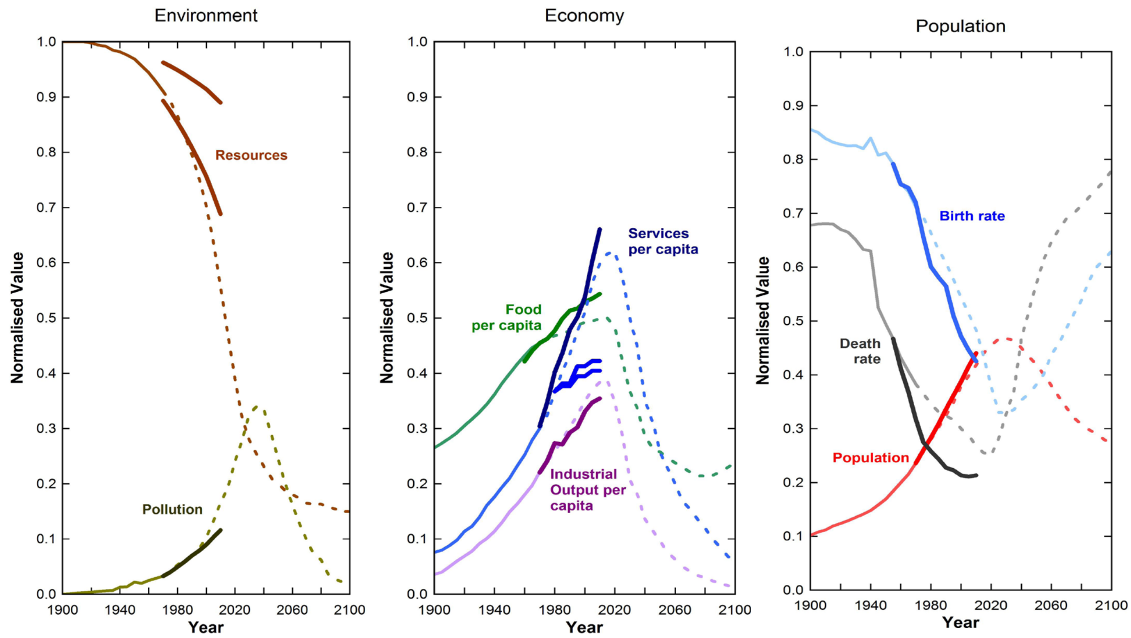

Figure 1. *LTG* BAU (Standard Run) scenario (dotted lines) compared with historical data from 1970 to 2010 (solid lines)—for demographic variables: population, crude birth rate, crude death rate; for economic output variables: industrial output per capita, food per capita, services per capita (upper curve: electricity p.c.; lower curves: literacy rates for adults, and youths [lowest data curve]); for environmental variables: global persistent pollution, fraction of non-renewable resources remaining (upper curve uses an upper limit of 150,000 EJ for ultimate energy resources; lower curve uses a lower limit of 60,000 EJ [Turner 2008]).

Regardless of the explanation, the level of global pollution is sufficiently low (in all scenarios, and the data) to not have a serious impact on the environment and human life-expectancy (Turner, 2008).

In contrast, of the two data curves of non-renewable resources remaining, the lower estimate demonstrates a closer alignment with the BAU (while the upper estimate aligns well with the comprehensive technology scenario [Figure 1]). The lower estimate also shows a significant fall toward the point when the World3 model incorporates a growing diversion of capital toward the resource sector in order to extract more difficult resources (50–60 per cent of the original resource; see Meadows et al., 1974, figure 5-18). This is the primary cause of collapse in the BAU scenario, as described above. The observed data is based on energy resources (see discussion in Turner 2008, pp. 405-407), conservatively assuming full substitution potential among the different primary energy types. This assumption may not be entirely accurate (for instance, in the case of transport fuels (primarily oil) essential for the smooth functioning of the economy). Subsequent sections reflect upon this question further.

Confidence through calibration

The striking comparison described above indicates that the original *LTG* work should not be dismissed as many critics have attempted to do, and increases confidence in the *LTG* scenario modelling. It is notable that there does not appear to be other economy-environment models that have demonstrated such comprehensive and long-term data agreement. Nevertheless, this agreement is not a complete validation of the model (partly due to the non-linear nature of the World3 model) or the BAU scenario. Achieving validation requires at least that key inputs and non-linear (or threshold) assumptions also be verified. This verification is partially initiated below with an examination of the imposts of resource extraction.

Despite the non-linearity of the World3 model, the general outcomes of the scenarios are not sensitive to reasonable uncertainties in key parameters (Meadows et al., 1974). Nevertheless, critics continue to question the value of the *LTG* modelling based on perceived model sensitivity (Castro, 2012). Superficially, early sensitivity analysis of the World3 model (de Jongh, 1978, Vermeulen and de Jongh, 1976) appeared to show that the model is sensitive to parameter changes. For example, by imposing a 10 per cent change from 1970 onwards to three parameters in the industrial sector it is possible to alter significantly the trajectories of the World3 output. In reproducing this change, I found that the outcome was not avoidance of overshoot and collapse, contrary to the critics' claim (Turner, 2013). Instead, a wider examination of outputs indicates that overshoot and collapse was simply delayed, and that the underlying reason for this was that industrial output per capita (a proxy for material wealth) remained constant for decades before declining. In effect, the critics were actually creating elements of the 'stabilized world' scenario where material consumption was restrained, but they did not acknowledge this.

Further, claims of parameter sensitivity evidently contradict the forty year alignment of the *LTG* model with independent data; if the model was over-sensitive it should not successfully forecast outcomes. The key to resolving this apparent paradox is to recognise that the World3 model was calibrated as a whole system against data and trends from 1900 to 1970. This calibration is not simply inferring parameter values from the available data—which is recognised by everyone including the *LTG* authors to incorporate sizable uncertainties—but more importantly that the various model outputs (population, food, resources, etc.) must simultaneously produce reasonable values against observed data. One sub-system of the model may work as an effective check on other sub-systems. The whole-system calibration then constrains the collected values that parameters can have. This is not to say that any single parameter is now known more accurately, which they are not. Rather, it is the collection of interactions that matters. This is a key point that Bardi (2011) makes in his review of earlier criticisms of the *LTG* (ie. the importance of treating a system as a whole and not isolating sub-systems without reference to the rest of the system).

Additionally, there are general principles of control systems which apply despite parameter sensitivity or uncertainty around the specifics of future system trajectories. It is a general property of systems with self-reinforcing and self-correcting mechanisms (ie. positive and negative feedbacks, the former producing growth) that they will overshoot their long-term equilibrium if there are sufficient delays in recognising or responding to the negative signals. Should this be the case, it is inevitable that the system will "correct" by falling or collapsing below that equilibrium.

Is collapse likely, and imminent? Examining mechanisms behind the near-term BAU collapse

Based simply on the comparison of observed data and the *LTG* scenarios presented above, and given the significantly better alignment with the BAU scenario than the other two scenarios, it would appear that the global economy and population is on the cusp of collapse. This contrasts with other forecasts for the global future (eg. Raskin et al., 2010, Randers, 2012), which indicate a longer or indeterminate period before global collapse; Randers for example forecasts collapse after 2050, largely based around climate change impacts, with features akin to the *LTG* comprehensive technology scenario. This section therefore examines more closely the mechanisms behind the near-term BAU collapse and explores whether these resemble any real-world developments.

Real world developments—Peak Oil

Having confirmed the significant alignment of 40 years of data with the BAU scenario, and established that the model is not inappropriately sensitive, this section now considers whether the key dynamics underlying the breakdown described above resemble actual developments. Since the collapse in the BAU scenario is predominantly associated with resource constraint and the diversion of capital to the resource sector, it is pertinent to examine peak oil (or other resource peaks). Peak oil refers to the peak in production of oil (particularly from conventional supply), as opposed to demand which is generally assumed to increase. Publications on peak oil have flourished in recent years as the possibility of a global peak has become more widely accepted (eg. by the otherwise conservative International Energy Agency) (Alexander, 2014). These publications tend to focus on the question of when the peak will occur and what the oil supply volume will be. Sorrel et al. (2010a, 2010b) review many of these and find that independent researchers generally expect peaking to occur within about a decade, or to have occurred recently (Sorrell et al. 2010a, Sorrell et al. 2010b, Murray and King, 2012); estimates of peaking made by oil industry representatives tend to be decades away. Unfortunately, these oil production profiles themselves say little analytically about the implications of reduced oil supply rates on the economy, though qualitatively a constrained supply of ubiquitous transport fuel is likely to be deleterious to the global and national economies (Hirsch, 2008, Friedrichs, 2010).

It is useful to compare the general qualities of past and future oil production with that inferred from the *LTG* BAU output (Figure 2), even though there is inevitable uncertainty around individual forecasts of oil production. The *LTG* production rate was derived by taking the first derivative of the non-renewable resource data.

The *LTG* curve approximates a "Hubbert-like" profile, depicted in Figure 2 using a logistic function (normalised to the same cumulative production ie. area under the curve). Hubbert assumed a finite resource, with exponential growth in production in the early production phase (based on data trends), and some mimic of discovery rates (ie. peaking and decline) leading eventually to zero production (Hubbert, 1956). He originally drew arbitrary curves based on postulating peak production rates, and estimates of ultimate resource. Subsequently, Hubbert used the more mathematically convenient logistic function (for cumulative production) to capture the qualitative properties of production profiles (Hubbert, 1982).

In comparison, oil production rates from actual and projected data do not peak and fall so rapidly, although the data superficially indicate a much lower peak as a result of the "accelerated" production or earlier peak between 1960 and 1985. The extra production (relative to *LTG*) in this period very closely matches the deficiency in production (relative to *LTG* between 1990 and 2005). Indeed, the cumulative production at 2005 is just 1 per cent different. The projection of oil production is based on an empirical model of production lagging discovery (Gargett and BITRE, 2009), where cumulative production cannot be greater than cumulative discoveries. Therefore, if discoveries have peaked and fallen, production must also do so, though the actual rates can of course differ. It takes no account of the how demand might vary, in contrast to the *LTG*.

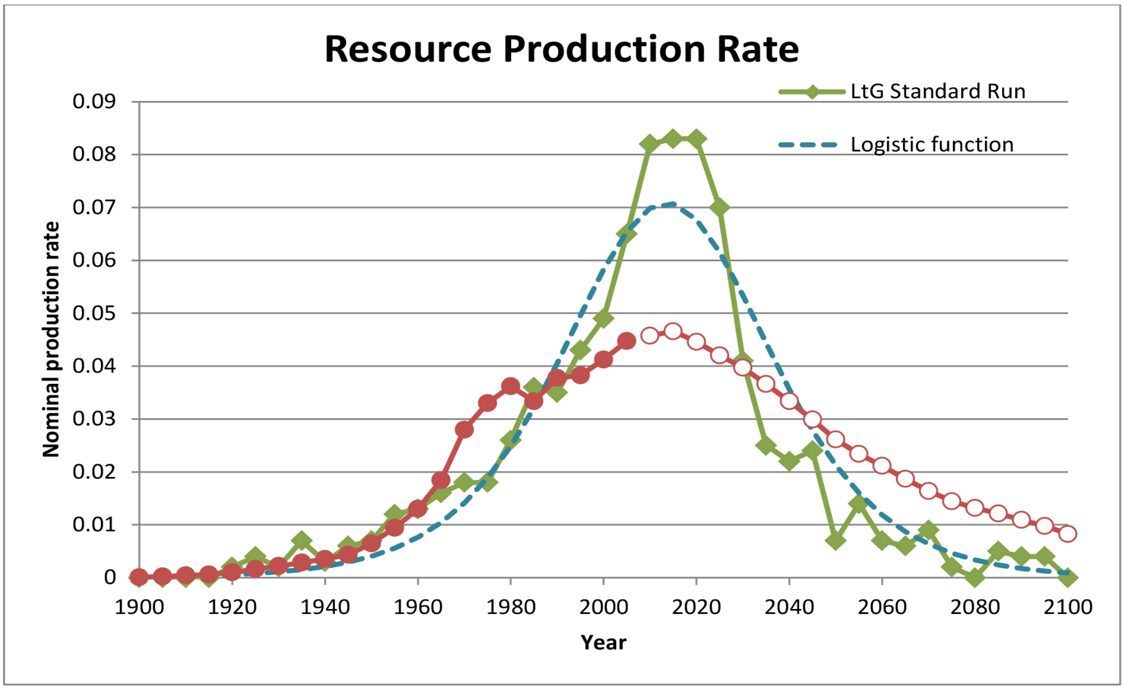

Figure 2. Oil production rate: actual and projection; derived from the *LTG*; and a "Hubbert-like" curve based on a logistic function - all normalised to equal total resource (ie. area under the curves).

Unlike other projections of oil production, the *LTG* curve is not hardwired explicitly in the model, but is an outcome of other dynamics. Exponential growth occurs initially because of the demand from exponentially growing industrial activity. Production subsequently falls due to the collapse in demand from industrial activity (see next section). Production of non-renewable resources in the World3 model scales with population using a per capita resource usage multiplier, and the latter is an increasing (approximately linear) function of industrial output per capita. Consequently, the production rate follows the industrial output.

Notably the oil resource has not run out when the global collapse begins; far from it, since the peak extraction rate occurs about halfway through the resource pool. Further, as respected commentators (*The Economist* and *The Guardian*) point out, there are immense additional pools of fuels in the form of unconventional oil and gas reserves, such as those being accessed by hydraulic fracturing (fracking) (Maugeri, 2012). (These additional reserves were included in the data of non-renewable resources for the comparison shown in Figure 1). The optimistic view being expressed recently is that there could be a new oil and gas glut. This superficially appears to contradict the resource constraint that underpins the collapse in the BAU scenario of the *LTG*.

But the protagonists of oil and gas gluts have not understood a crucial point. They have essentially confused a stock with a flow. The key, as the *LTG* modelling highlights, is the rate at which the resource can be supplied, ie. the flow, and the associated requirements of machinery, energy and other inputs required to achieve that flow. Contemporary research into the energy required to extract and supply a unit of energy from oil shows that the inputs have increased by almost an order of magnitude. It does not matter how big the resource stock is if it cannot be extracted fast enough or other scarce inputs needed elsewhere in the economy are consumed in the extraction. Oil and gas optimists note that extracting unconventional fuels is only economic above an oil price somewhere in the vicinity of US$70 per barrel. They readily acknowledge that the age of cheap oil is over, without apparently realising that expensive fuels are a sign of constraints on extraction rates and inputs needed. It is these constraints which lead to the collapse in the *LTG* modelling of the BAU scenario.

The end of easy oil, and subsequent global collapse

Consequently, what is more relevant than the oil supply rates per se to our analysis of the *LTG* and collapse is the "opportunity cost" associated with extracting diminishing supplies of conventional oil or difficult extraction of non-conventional oil (eg. tar sands, deep water, coal-to-liquids, etc.) (Murray and King, 2012). In the *LTG*, the fraction of capital allocated to obtaining resources (FCAOR) represents this opportunity cost. In the peak oil literature, the relevant measure of opportunity cost is the energy return on investment (EROI) which is related to the net energy available after energy is used extracting the resource (Heun and de Wit, 2012, Dale et al., 2011, Heinberg, 2009, Murphy and Hall, 2011). The EROI is defined as the ratio of gross energy produced, TE_{Prod}, to energy invested to obtain the energy produced, E_{Res}.

$$EROI = \text{energy return on (energy) invested} = \frac{TE_{Prod}}{E_{Res}}$$

The EROI can be related to the FCAOR used in the *LTG*. Since the capital (machinery eg., pumps, vehicles) operated in the resource sector, C_{Res}, is basically representative of the overall machinery stock, C_{Ttl}, the energy intensities will be similar and therefore the ratio of capital can be approximated by the ratio of energy used in the resource sector, E_{Res}, to total energy consumed, TE_{Cons}.

$$FCAOR = \text{fraction of capital allocated to obtaining resources} = \frac{C_{Res}}{C_{Ttl}} \approx \frac{E_{Res}}{TE_{Cons}}$$

Since the total energy consumed in any year will be approximately equal to the total energy produced (because stocks of energy stored are relatively small and don't change significantly from year to year) $TE_{Cons} \approx TE_{Prod}$, then equations 1 and 2 give:

$$FCAOR = \frac{1}{EROI}$$

The collated data and model of EROI in Dale et al. (2011) can therefore be converted to FCAOR at corresponding values for the fraction of the oil resource remaining. This can be then be compared against the data used in the *LTG* (eg. shown in Meadows et al., 1974, figure 5-18). If the peak of conventional oil has occurred, or is about to occur, then approximately half the resource has been consumed, ie. non-renewable resource fraction remaining, NRFR ≈ 0.5. Contemporary estimates of EROI are in the range 10-20 (or 1/EROI of 0.1-0.05). This agrees with the values and trends of the key parameter, FCAOR, used in the *LTG* (see Figure 3).

Therefore, in addition to the data comparison made for modelled outputs, this data on oil resource extraction corroborates a key driver of dynamics in the *LTG* BAU scenario. In other words, in addition to outputs of the model aligning with data, the key mechanism driving the collapse in the BAU is also observed in real world data.

The limited role of alternative energy innovation

Given that the key mechanism underlying collapse in the BAU scenario is evidently the diversion of capital toward extracting depleting resources, it is pertinent to examine the sensitivity of the scenario to changes in this factor. In the case of oil (and gas) resources in particular, could it be that the current expansion of unconventional resources (tight oil, shale oil and gas, tar sands, etc.) is sufficient to offset the decline in production of conventional oil? Critics of unconventional resources point toward decreasing net energy due to the difficulty of extraction. In terms of the *LTG* modelling, this relates to the fraction of capital allocated to obtaining resources (FOCAR) increasing as the resource stock reduces (such as in the BAU setting). However, it is early days in the new play of unconventional resources, so it would be reasonable to anticipate that cumulating experience and new technologies will ease the extraction task and hence reduce the energy/capital required for each barrel of oil. This possibility has been tested in the World3 model, using the setting (testFOCAR) shown in Figure 3.

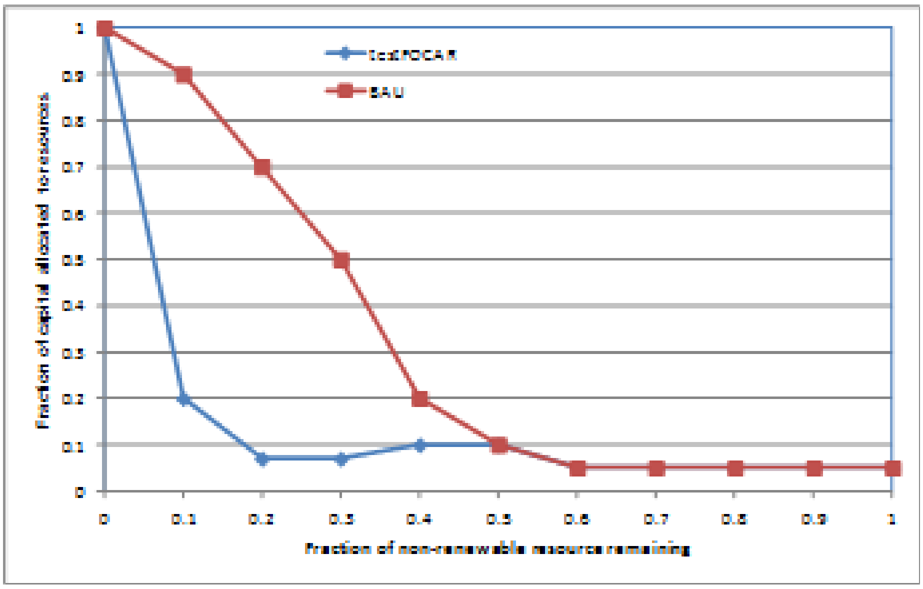

Figure 3. Increased efficiency in extraction of unconventional resources (blue curve) as the fraction of resource declines toward zero, compared with the BAU setting (red).

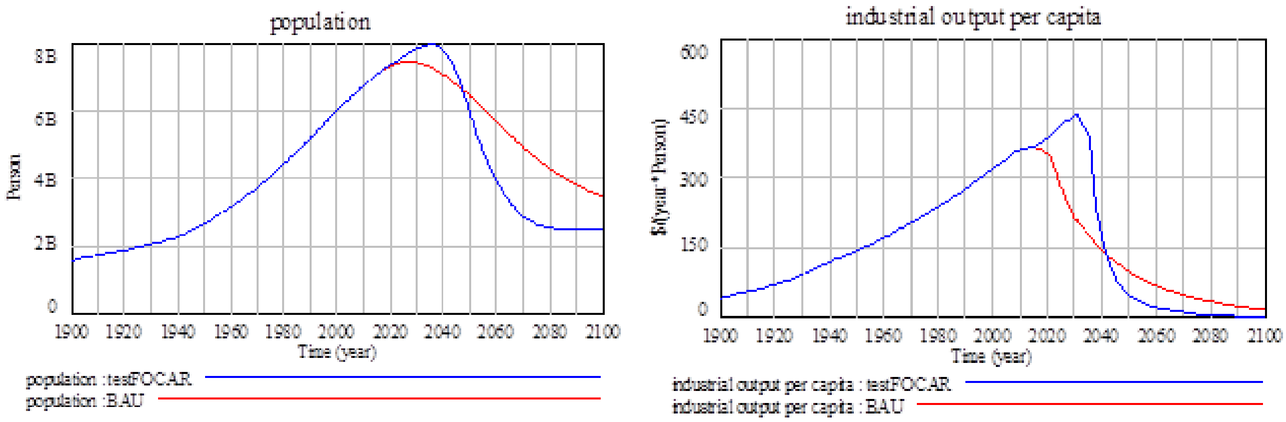

Figure 4. Collapse delayed by about 2 decades, but is worse (ie. a "Seneca cliff"), due to increased efficiency in accessing unconventional resources.

The alternative FOCAR is held at current levels and even slightly decreased (to half-way between the original 5 per cent and current level) to simulate the effect of cost saving technologies. But as the resource remaining approaches 10 per cent, the extraction effort increases and must approach a FOCAR of 1 as the resource is exhausted (the value of 1 actually prevents the non-renewable resource from being completely exhausted because the economic costs of harvesting resources effectively slows the resource extraction rate). This type of FOCAR was also tested by the *LTG* team (see pp. 398–405 Meadows et al., 1974) among other sensitivity tests.

However, collapse is not avoided but simply delayed by one to two decades (Figure 4), and when it occurs the speed of decline is even greater. Easier to obtain resources permit economic growth to be re-kindled following a relatively minor hiatus at about 2015. Subsequently, the draw-down of non-renewable resources continues apace, and reaches such a low level that the industrial system cannot be supported and output drops rapidly at about 2030. As a result, population grows a little higher than the BAU, but falls from about 2035 at a faster rate and to a lower level.

Contemporary impacts of oil constraints: is collapse underway?

The close alignment between the *LTG* BAU scenario and observed developments over the last four decades, as well as the correspondence in the underlying dynamics described above, portend of potential global collapse. Although the general commentary on the *LTG* describes collapse occurring sometime mid-century (and the *LTG* authors stressed not interpreting the time scale too precisely), the BAU scenario implies that a relatively rapid fall in economic conditions and the population could be imminent. Indeed, other aspects of oil supply constraints explored in the following, indicate that the ongoing economic downturn of the GFC may be representative of an imminent BAU style collapse.

Firstly, oil price rises have been linked to recent increases in food prices (eg. (Alghalith, 2010, Chen et al., 2010). There are direct and indirect links between oil and food (Schwartz et al., 2011, Neff et al., 2011), associated with fuel for machinery and transport, both on-farm and in processing and distribution, as well as feedstock for inputs such as pesticides. Also, although nitrogen fertilizer is largely manufactured from natural gas, the price of these commodities is also linked to that of oil. More recently, production of bio-fuel as an alternative transport fuel, such as corn-based ethanol, has displaced food production and has been a factor in food price increases (eg. Alghalith, 2010, Chen et al., 2010). These developments resemble the dynamics in the *LTG* BAU scenario where agricultural production is negatively affected by reduced inputs. There may also be evidence of global pollution beginning to impact food production (which is a secondary factor in the BAU scenario) in the recent occurrence of major droughts, storms and fires (eg. Russia, Australia) that are potentially early impacts of global climate change driven by anthropogenic greenhouse gas emissions.

The role of oil (and food) prices extends further, into more general economic and political shocks. For instance, other aggregate modelling of the role of energy in the economy (Nel and Cooper, 2009) finds that energy constraints cause a long-term economic downturn, as well as reducing greenhouse gas emissions, which are similar outcomes to those in the *LTG* collapse. Empirically, there is clear evidence (eg. Murray and King, 2012, overviews in Murphy and Hall, 2010, Murphy and Hall, 2011) of a connection between many oil price increases and economic recessions (just as there exists a strong correlation between energy consumption and growth in economic indicators). Hamilton's econometric analysis (2009) indicates that the latest (US) recession, associated with the GFC, was different from previous oil-related shocks in that it appears caused by the combination of strong world demand confronting stagnating world production. His analysis downplays the role of financial speculation.

Nevertheless, the overriding proximate cause of the GFC is evidently financial: excessive levels of debt (relative to gross domestic product (GDP), or more accurately, the actual capacity of the real economy to pay back the debt) (Keen, 2009). Such financial dynamics were not incorporated in the *LTG* modelling. Das (2011) highlights correlated defaults in high-risk debts, such as sub-prime housing mortgages, as a key trigger of the GFC. The financial models used did not properly account for a high number of defaults occurring simultaneously, being based on statistical analysis from earlier periods which suggest less correlation in defaults. Correlation may be caused by specific aspects of the financial instruments created recently, including for example, adjustments upward in interest rates of sub-prime mortgages after an initial "teaser" period of negligible interest rates. Even so, some spread in defaults would be expected in this case. Alternatively, another potential factor could be the price increases in oil and related commodities, which would be experienced by all households simultaneously (but with a disproportionate impact on large numbers of households with low discretionary income) and hence cause the coordinated debt defaults.

Regardless of what role oil constraints and price increases played in the current GFC, a final consideration is whether there is scope of a successful transition to alternative transport fuel(s) and renewable energy more generally. Due to the GFC, there may be a lack of credit for funding any coordinated (or spontaneous) transition (Fantazzini et al., 2011). And economic recovery may be interrupted, repeatedly, by increased oil prices associated with any recovery. Additionally, even if a transition is initiated it may take about two decades to properly implement the change over to a new vehicle fleet and distribution infrastructure (Hirsch, 2008, Hirsch et al., 2005). To transition requires introducing a new transport fuel to compensate for possible oil production depletion rates of four per cent (or higher) while also satisfying any additional demand associated with economic growth. It is unclear that these various conditions required for a transition are possible.

The role of social responses

In terms of social changes, it is pertinent to note that while the authors of the *LTG* caution that the dynamics in the World3 model continue to operate throughout any breakdown, different social dynamics might come to prominence that either exaggerate or ameliorate the collapse (eg. reform through global leadership, regional or global wars). Other researchers have contemplated how society might respond to serious resource constraints (eg. Friedrichs, 2010, Fantazzini et al., 2011, Heinberg, 2007, Orlov, 2008, Heinberg, 2011). Various degrees of hostility are foreshadowed, as well as lifestyles in developed countries that revert to greater self-reliance.

The dynamics in the World3 model leading to collapse resonate with aspects of other conceptual accounts of failed civilizations (Tainter, 1988, Diamond, 2005, Greer, 2008, Greer, 2005). Tainter's proposition of diminishing returns from growing complexity relates to the increasing inefficiency of extracting depleting resources in the World3 response. It also aligns with a more general observation in the *LTG* that successive attempts to solve the sustainability challenges in the World3 model, which lead to the comprehensive technology scenario, result in even more substantial collapse. The existence in World3 of delays in recognising and responding to environmental problems resonates with key elements in Diamond's characterisation of societies that have failed. And Greer's mechanism of "catabolic collapse" - ie. increases in capital production outstripping maintenance, coupled with serious depletion of key resources - describes in a slower mode the core driver of breakdown in the *LTG* BAU.

Unfortunately, scientific evidence of severe environmental or natural resource problems has been met with considerable resistance from powerful societal forces, as the long history of the *LTG* and international UN initiatives on environmental/climate-change issues clearly demonstrate. Somewhat ironically, the apparent corroboration here of the *LTG* BAU implies that the scientific and public attention given to climate change, whilst tremendously important in its own right, may have deleteriously distracted from the issue of resource constraints, particularly that of oil supply. Indeed, if global collapse occurs as in this *LTG* scenario then pollution impacts will naturally be resolved—though not in any ideal sense! A challenging lesson from the *LTG* scenarios is that global environmental issues are typically intertwined and should not be treated as isolated problems. Another lesson is the importance of taking pre-emptive action well ahead of problems becoming entrenched. Regrettably, the alignment of data trends with the *LTG* dynamics indicates that the early stages of collapse could occur within a decade, or might even be underway. This suggests, from a rational risk-based perspective, that we have squandered the past decades, and that preparing for a collapsing global system could be even more important than trying to avoid collapse.

Appendix

Updates to the historical data

The data presented here follows that of the thirty year review (Turner, 2008). This data covers the variables displayed in the *LTG* output graphs: population (and crude birth and death rates); food supply per capita; industrial output per capita; services per capita; fraction of non-renewable resources available; and persistent global pollution. Data sources are all publically available, many of them through the various United Nations organisations (and websites). Details were provided earlier (Turner, 2008) on these data sources and aspects such as interpretation, uncertainties and aggregation. However, some additional data and calculation were necessary since measured data to 2010 was not always available (and even when it is the data may be forecast estimates). A summary of the data is provided in the following.

Population data is readily available from the Population Division of the Department of Economic and Social Affairs of the UN (United Nations) Secretariat (obtained via the online EarthTrends database of the World Resources Institute); but data from 2006 onwards is a forecast. Given the short gap to 2010 and typical inertia in population dynamics, the 2010 estimate will be sufficiently accurate for the comparison made here.

Food supply was based on energy supply data (calories) from the Food and Agriculture Organisation (FAO), with the extension to 2009/10 generated from comparison with production data, which was scaled to the energy supply data for each corresponding food type in the production data.

Industrial output was available only to 2007 directly from the UN Statistical Yearbooks (UN 2006, 2008), now accessible online. Industrial output per capita is used as a measure of material wealth in the *LTG* modelling, but the industrial output also supplies capital for use in other sectors, including agriculture and resource extraction.

Service provision (per capita) has been measured by proxy indicators: electricity consumed per capita and literacy rates. In the former case, for the most recent data it was necessary to scale electricity generation data (from BP Statistical Review 2011) to consumption values and hence account for electricity transmission losses. Literacy rates were updated from the United Nations Educational, Scientific and Cultural Organisation (UNESCO) Statistics database, which is the source for the EarthTrends data. Literacy rates provide a partial proxy indicator since they will saturate as they increase toward 100 per cent. Values are provided for time ranges rather than single years.

The fraction of non-renewable resources available is estimated from production data on energy resources, since other resources are conservatively assumed to be infinitely substitutable or there to be unlimited resources. Energy production data to 2010 was obtained from the BP Statistical Review (2011), which was subtracted from the ultimate resource originally available to obtain the remaining resources. To account for considerable uncertainty in the ultimate resource, upper and lower estimates were made based on optimistic and constrained assessments, respectively (Turner, 2008). Hence, two data curves are provided for the fraction of non-renewable resources remaining.

Finally, global persistent pollution was measured by the greenhouse gas CO2 concentration, available to 2008 on the EarthTrends database, with latest measurements to 2010 from Pieter Tans, National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL), and Ralph Keeling, Scripps Institution of Oceanography.

Data comparison with three bounding scenarios

To help convey how significant is the strong alignment of data with the BAU or "standard run" scenario, with this expands the comparison to two other key scenarios from the *LTG* modelling, namely the "comprehensive technology" and "stabilized world" scenarios. The three scenarios together effectively present a bounding envelope for the full spectrum of scenarios produced.

The comprehensive technology scenario attempts to solve sustainability issues with a broad range of purely technological solutions. This technology-based scenario incorporates levels of resources that are effectively unlimited, 75 per cent of materials are recycled, pollution generation is reduced to 25 per cent of its 1970 value, agricultural land yields are doubled, and birth control is available world-wide.

For the "stabilized world" scenario, both technological solutions and deliberate social policies are implemented to achieve equilibrium states for key factors including population, material wealth, food and services per capita. Examples of actions implemented in the World3 model include: perfect birth control and desired family size of two children; preference for consumption of services and health facilities and less toward material goods; pollution control technology; maintenance of agricultural land through diversion of capital from industrial use; and increased lifetime of industrial capital.

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[i] One particularly important case in point is the change from elastic to inelastic supply of oil and the resulting economic implications (Murray and King, 2012, Murray and Hansen, 2013), which are discussed in detail in later sections.

[ii] The statistical analysis undertaken in our 30-year review (Turner, 2008) was not reproduced here as the changes would be minor, and add little further to the assessment.

[iii] http://earthtrends.wri.org (source: www.un.org/esa/population/ordering.htm)

[iv] http://faostat3.fao.org/home/index.html#DOWNLOAD_STANDARD

[v] UN 2006, table 5, p. 22, UN 2008, table 5, p. 14. http://unstats.un.org/unsd/syb/

[vi] http://stats.uis.unesco.org/unesco/TableViewer/document.aspx?ReportId=136&IF_Language=eng&BR_Topic=0

[vii] www.esrl.noaa.gov/gmd/ccgg/trends/, scrippsco2.ucsd.edu/

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