On production and abatement time scales in sustainable development. Can we loosen the *sustainability screw*?

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Outline

1. Introduction
2. System Dynamics
3. Results
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We explore a time scales’ conjecture in the context of sustainability:

Any reasonable notions of sustainability must include a suitable synchronisation of time scales

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Synchronisation of time scales of processes of **human development** and those of the **natural environment**
Variables

- **Time**: $t \in [0, \infty)$.  
- Non-renewable resource: $M(t) \in \mathcal{R}_+, \forall t$.  
- Renewable resource: $R(t) \in \mathcal{R}_+, \forall t$.  
- Production capacities: $K(t) \in \mathcal{R}_+, \forall t$.  
- Abatement capital: $Q(t) \in \mathcal{R}_+, \forall t$.  
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The Model Equations

\[ \dot{M} = -\varphi_M M + Ce^{-\delta t} \quad (1) \]

\[ \dot{R} = \sigma \left( -R + \frac{\gamma}{1 + be^{-\alpha R}} \right) - \varphi_R R + \gamma_Q Q \quad (2) \]

\[ \dot{K} = \varphi_M M + \varphi_R R - (\varphi + \psi_K + \kappa_K) K + \varphi_H H \quad (3) \]

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Dynamics of Non-renewable resources

\[ \dot{M} = -\varphi_M M + Ce^{-\delta t} \]

- All the coefficients are positive, i.e., \( \varphi_M > 0, C > 0, \delta > 0 \).
- \( M \) is a diminishing variable, by its very nature. However, due to discovery, it may temporarily grow.
- The amount \( \varphi_M M \) represents the non-renewable resource contribution to the growth of production capital \( K \).
- The exogenous term \( Ce^{-\delta t} \) represents the yet to be discovered resource; its long run value is zero due to the non-renewable nature of these resources.
- If no new resources are discovered then \( M(t) \) decays exponentially, at a constant rate \( \varphi_M \).
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The 2nd Equation

Dynamics of Renewable resources

\[ \dot{R} = \sigma \left( -R + \frac{\gamma}{1 + be^{-\alpha R}} \right) - \varphi R R + \gamma Q Q \]

- The dynamics of this variable is such that, if unperturbed and not too much, depleted, it should converge to some pristine value \( \bar{R} \) (probably once attained in the remote past).
- On the other hand, the resources availability will worsen if certain level of “pollution” is exceeded and the resources lose the capacity to renew.
- In the latter case, we expect \( R \) to converge to some low value \( \underline{R} \). This indicates a bifurcation in the homogenous solution to an equation for \( R \) (at some critical level \( R_c > 0 \)).
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\[ \dot{R} = \sigma \left( -R + \frac{\gamma}{1 + be^{-\alpha R}} \right) - \varphi_R R + \gamma_Q Q \]

- Coefficient \( \sigma > 0 \) weighs the strength, with which \( R \) follows the convergence paths to \( \overline{R} \) or \( \underline{R} \), relative to the other effects (i.e., “intra-systemic” effects).
- Positive constants \( \gamma, b, \alpha \) describe the logistic growth function for \( R \). The amount \( \varphi_R R \), \( \varphi_R > 0 \) represents the renewable resource contribution to growth of production capital \( K \).
- \( \gamma_Q Q \) represents the positive impact of abatement capital on the resource renewal.
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Dynamics of Production Capacities

\[ \dot{K} = \varphi_M M + \varphi_R R - (\varphi + \psi_K + \kappa_K)K + \varphi_H H \]

- When fully utilised, then $K$ might reflect consumption.
- All coefficients $\varphi, \psi_K, \kappa_K, \varphi_H$ are non-negative. In particular, $\varphi > 0$ characterises the depreciation rate of $K$.
- Quantities $\psi_K K$ and $\kappa_K K$ represent the capital sector’s contributions to the growth of abatement capital and of human capital, respectively.
- The amount $\varphi_H H$ captures the production capital’s intensification attributable to human capital.
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The dynamics of abatement capital is assumed to be linear.

Further, we assume that \( Q \) grows at a rate that is proportional to the production capital \( K \) and is depreciated at a rate proportional to its own size.

Purpose of abatement is to alleviate pressures placed on the renewable resources by the production processes. (Higher the abatement, lower the pollution, and hence less pressure on renewable resources).
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Initially, we assume \( c(R, K) = \text{const} > 0 \). (This reflects our view that most of people who constitute (or will constitute) human capital in a “medium-term” planning horizon period (say, 30 - 50 years) have already been born).

A possible function, reflecting dependence of \( c(R, K) \) on natural resources, could be

\[
c(R, K) = c_0 \left( 1 + \frac{R - R_0}{R_0} + \frac{K - K_0}{K_0} \right), \quad c_0 \geq 0
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The 5th Equation

Dynamics of Human Capital

\[ \dot{H} = a \left( 1 - \frac{H}{c(R, K)} \right) H \]

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We considered oil reserves as a proxy for $M$ (Non-renewable resources).

Biocapacity of earth served as proxy for $R$ (Renewable Resources or State of Environment).

World GDP (Gross Domestic Product) as proxy for production capital $K$.

World’s working age population for $H$, (Human Capital).

Abatement $Q$ is assumed to grow with $K$, albeit, not with the same velocity. [only partial data on this was available].
Proxies

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The state variables assume known values
\[ M_0 = 1, \quad R_0 = 1, \quad K_0 = 1, \quad Q_0 = 1 \quad \text{and} \quad H_0 = 1 \]
at some initial time \( t = 0 \) (after suitable normalization).

Because...
Interest here is to capture the variation in variables, rather than in their absolute levels.

The starting point of the runs
The initial time is identified as year 2000. The opening fragments of the calibrated runs correspond to their respective historical data.
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The initial time is identified as year 2000. The opening fragments of the calibrated runs correspond to their respective historical data.
‘Business as usual’ time path

rapid growth for 10 years (~7% p.a.) then disaster
The ‘business as usual’ trajectory in \((K, R, M)\) space.

- Resembles thread of a screw.
- Trajectory spiraling down to a state of low resources, low capitals.
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Trajectory spiraling down to a state of low resources, low capitals.
The ratio

\[ \Delta = \frac{\phi_M + \phi_R + \phi_H}{\gamma Q} \]

The numerator is a sum of coefficients that describe the amounts of resources (non-renewable, renewable and human) utilised for growth of production capital \( K \).

The denominator, \( \gamma Q \) describes how much production capital is devoted to help regrow renewable resources.

The larger the numerator, the faster \( K \) increases; the larger the denominator, the faster the renewable resources recover.
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\( \Delta \) could be regarded as the ratio of the “intensity of production effort” over the “intensity of abatement effort”.

We conjecture that \( \Delta \) conveys information on how human and natural processes are synchronised, and influences the relative time scales of production and natural recovery processes.

In particular, larger values of \( \Delta \) will signify that growth of \( K \) dominates that of \( R \).

\( \Delta = 6.8571 \) corresponds to ‘business as usual’ scenario.
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Bifurcated sustainability screws

If $\varphi_R$ is reduced by its 1/3rd in year 2009 (slower exploitation of Renewable Resources): $\Delta = 5.1905$
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- Green is the averted screw, while the red is with business as usual.
- Averted screw approaches to a state of high capitals and high renewable resources.
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\[ \Delta = 5.1905 : \text{time path of the variables} \]
Dedicating less renewable resources to production $K$ has an immediate negative effect on growth $K$ [might be perceived by some as a “negative” modification].

As more renewable resources $R$ become available, they feed into the growth process of capital that quickly recovers and overtakes the path corresponding to the business-as-usual scenario.

After $R$ is stabilized at the “high” steady state, production capital $K$ also grows substantially.

This results in the high abatement capital $Q$ that helps renewable resources $R$ remain in the high steady state.
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What’s happening there...

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- The **Blue** one is the averted screw, while the **red** is with business as usual.
- Again, averted screw approaches to a state of high capitals and high renewable resources.
To avoid being collectively screwed by the “sustainability screw”, we should all campaign for synchronisation of time scales of human development and natural processes.