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Getting Physical: Providing a Physical Basis for Economic Growth Analyses to Fill the Information Gaps in Contemporary Economics for Policy Development for a Sustainable Global Economy

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Abstract

Prevailing economic theory is based on many hypotheses which have no physical science basis. The physical information missing from current practice currently undermines the successful development of policies for transitioning the global economy to a more resource efficient form that better sustains the natural capital its uses for future growth. This paper begins with a review of the state of the relevant art on economic behavior in physics and biology and how to transfer that knowledge to global economic models. The physical basis of economic growth arises from resource acquisition behaviour for growth in biology and this paper describes how that knowledge can be used to build a meaningful TPF and then TFP to describe growth. Without this information the risks to growth cannot be fully understood.

Keywords

Production, Sustainable Growth, Thermodynamic Systems Analysis, Climate Impact

1. Introduction

In classical economic view, economics has the purpose of resource distribution across society for the public good i.e. the common good. This definition of purpose arises from Adam Smith's combined work across both The Theory of Moral Sentiments (Smith, 1790) and An Inquiry into the Nature and Causes of the

Wealth of Nations (Smith, 1776).

This differs from the neo-classical re-interpretation but is the more accurate interpretation of Smith's work and his collaboration with David Hume. Smith's work is in essence a natural history approach to ethics and economics beginning with a distillation of ethical social behaviour down to empathy (mutual sympathy) in "Moral Sentiments", followed by an explanation of the role self-interest plays in how wealth is distributed in economic systems behaviour in "The Wealth of Nations".

It is no coincidence that neo-classical economics and neoliberal political theory tends to neglect The Theory of Moral Sentiments and focus on The Wealth of Nations when referencing the latter. Economic theory equating the economic common good with maximising individual wealth is logically incompatible with an analysis of Theory of Moral Sentiments and The Wealth of Nations as a common body of Smith's work. If The Theory of Moral Sentiments is neglected to obtain a partial view that supports any particular political or economic theory being advanced, there is critical missing information for the claim being made.

The question of how resources are distributed across society for the public good now has to be posed in a new physical context: that in which current global economic activity is currently comprehensively degrading natural capital, as defined in its wider scientific sense. Natural capital in that sense is the life-bearing capacity of the global environment and its life-supporting capability.

Returning to the work of Adam Smith in The Theory of Moral Sentiments (Smith, 1790) and The Wealth of Nations (Smith, 1776), in both works Smith is developing a natural philosophy for ethics in politics. We are now in a position where there is a body of natural science information, ranging from physics to psychology that more completely describes the issues presented in classical economics and fills the information gaps in classical economics and neo-classical economics.

To reconfigure current economic practice to meet the challenge of providing accurate poly-making risk assessments to meet the challenge of climate change and wider environmental and natural capital degradation, causation misinformation in existing economic practice needs to be replaced by natural science-based causation.

2. Method

My approach is based on Farmer's work in applying system analytics to economics (Farmer, 2024) by using J. Doyne Farmer's summary definition of economics:

'economics = accounting + behaviour' (Farmer, 2024)

as the basis for introducing a physical, thermodynamic basis for economics in terms of resource and value accounting and system behaviour. The strategy applied in this paper is to use a universal physical behaviour (thermodynamics) (Palmer, 2023a) applied to systems analytics for economic behavior, drawing on the best defined *production system behavior* in biology and ecology. Consequently, I will use resource acquisition for growth in biological systems as a reference point for resource acquisition behavior in production system as it has a physical, natural science basis that can be used to fill the physical information gap existing in contemporary economics. The biological and ecological behaviors referenced and used as a model for production in this paper are those which are most deeply understood in physical terms—those of the bacteria and archaea (collectively termed *prokaryotes*).

The boundaries on economic activity include those set by the second law of thermodynamics—Physical boundaries on energy and material resource use in economics—Equation (1):

$$W - E = T_0 \Delta S_{tot} \tag{1}$$

where W is the work done when system changes state, E is the total energy, T_0 is the environmental temperature and ΔS_{tot} is the change in entropy "S" (entropy being the dissipation of energy, materials and hence information into the environment).

Physical boundaries on use of information, including its use in economics—Equation (2):

$$H = B/T_0 \tag{2}$$

where H = Shannon measure of information (the missing information about the system), B = free energy (exergy) of the system and T_0 is the temperature of the systems environment) (Palmer, 2023a; Palmer, 2019). This physical basis for information is also captured in Landauer's principle (Palmer, 2023a; Palmer, 2019).

The full description of physical relationships between resource energy use, critical resource acquisition and production and growth in biology and its mathematical trajectories (mathematical descriptions) is provided in **Appendix**. **Appendix** also describes how fitness in biology is defined by the environment and the most fundamental environmental difference being critical resource limitation in comparison to lack of critical resource limitation.

Biological production descriptions incorporate all the critical physical aspects of manufactured economic production. For example, in multicomponent (manufacturing) production the rate-limiting material resources(s) determine the maximum rate of production. That includes all production resources (and includes use of information if thermodynamics is used). Economics is already adjusting previous assumptions of rational agency in equilibrium theory to describe market decisions based on a natural science (psychology) (Kahneman & Tversky, 1979; Kahneman, 2011) and is now beginning to assess economic behaviour on a systems basis (Farmer, 2024). Adding universal physical rules in the form of thermodynamics (as Robert Ayres has long advocated in economics) to system behaviour will complete filling in the current information gaps.

In practice production systems lack infinite resources so some form of limitation emerges mathematically from physical production as follows:

The general mathematical relationship (**Figure 1**) has a sigmoidal trajectory between production output (m_p) and production-critical resource(s) m_{rc} which is inherent in the biological production descriptions provided in detail in **Appendix** is as follows:

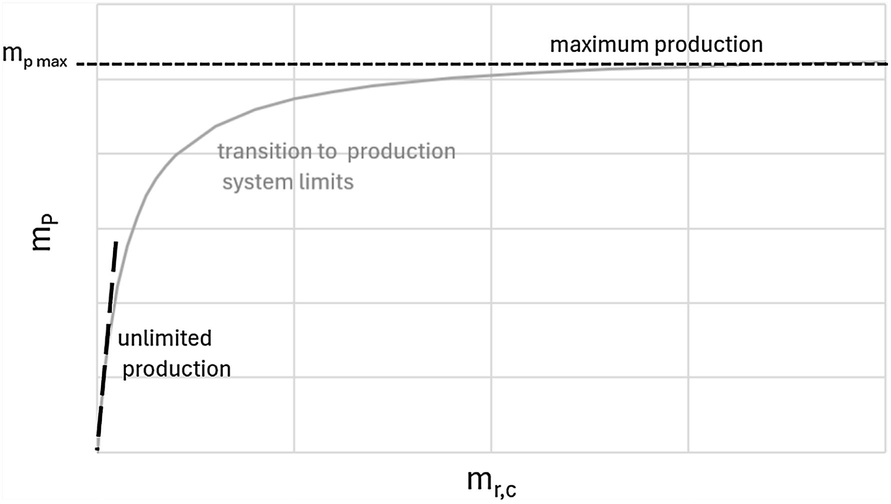


Figure 1. Physical production system description approach.

$$m_{p.max} = m_{rc} \big/ \left(k + m_{rc}\right)$$

where production output rate is m_p, m_{rc} is quantity of production-critical resource and k is the production coefficient for production m_p from m_{rc}.

Stated as the form arising in biological production this gives Equation (3):

$$\text{maximum rate of production} = \quad \rho = \rho_{max} \cdot r_c / k + r_c \tag{3}$$

The production relationships in biology also provide other critical information relating to production and its sustainability including the effect of entropy on production efficiency for which prokaryotes have "learnt" through environmental adaptation to invest more in production maintenance and storage of resources under conditions of resource limitation, hence Equations (4) and (5):

$$\text{deterioration in production system productivity} = \quad k_d = m \cdot Y_p \tag{4}$$

where k_d is deterioration in production system productivity over time and 'm' is the resource input into the maintenance needed to restore production to the maximum product yield per production system ($Y_{p\,max}$)

$$\text{product yield per production system} = \quad Y_p = Y_{p\,max} \Big/ \left(1 + m \cdot Y_{p\,max} / \rho\right) \tag{5}$$

where $Y_{p\,max}$ is the maximum product yield from the production system (usually at startup), Y_p is the product yield during the operating life of the production system, ρ is the production rate (product/unit time) and m is the resource input into the maintenance needed to restore production to the maximum product yield per production system.

To translate physical rules for production and productivity into a description of macroeconomic growth, a Technical Progress function needs incorporating into the macroeconomic growth description that includes the critical physical factors. Information utilization is critical to biological production (**Appendix**) and the critical output from Labour into production economy is information use (knowledge) and this must be captured for an accurate description of production potential e.g. Equation (6):

$$L = a\left(N \cdot Y_p\right) - b \tag{6}$$

Y_P is the product yield from the production system, "a" and "b" are Pareto cumulative distribution function constants, ρ is the production rate (product/unit time) and "m" is the energy and material input into the maintenance needed to restore production to the maximum product yield per production system.

Information is physical and has entropic consequences in its use i.e. the more complex a product is the more information utilization (knowledge) development and labour provision of that is required to innovate. This understanding of thermodynamic implications of knowledge development and use arises from the works of Lloyd and Pagel as expressed in Equation (7).

$$\mathcal{D}_r = \bar{S} - S_0 \tag{7}$$

Equation (7) provides a physical description of the complexity of anything, which physically is a function of its thermodynamic depth $\mathcal{D}_r$ which is proportional to the difference in entropy between the coarse grained entropy $\bar{S}$ of the system and its fine-grained entropy S_0 (see Section 4).

This relationship implies increased product complexity requires increased information utilization and increased depth of innovation to innovate to create new innovative products in an economy. Equation (7) provides a basis for the emergence of complex system signatures in production, such as a power-law distribution in TFP as proven by Sahal (Sahal, 1979; see section 3.4). A TFP with this level of capability is needed to produce a fully accurate Total Productivity Function (TPF) in a macroeconomic growth description.

An example of how to uprate a Modified Swan-Solow macroeconomic growth model to incorporate an appropriate Total (Sahal) TFP in physically accurate Total Productivity Function is provided in Equations (8)-(10) as follows.

Equation 8: Solow-Swan macroeconomic growth model:

$$Y(t) = \text{Total Production (GDP) for year } t;\ K(t)\alpha(A(t)L(t)(1-\alpha) \tag{8}$$

$Y(t)$ = Total Production (GDP) for year t; $K(t)$ = capital for year t, $L(t)$ = labour capacity for year t, $A(t)$ = technology productivity factor for year t and α = elasticity of output with respect to capital.

To fully describe GDP by accurately incorporating production this Swan-Solow Equation (8) needs updating with a Cobb-Douglas production function as follows:

$$Y = AL\beta K\alpha \tag{9}$$

Y = annual Total Production (real GDP); K = annual capital input, L = annual labour capacity (hours) year t, A = Total Factor Productivity (TFP), α = output elasticity of capital and β = output elasticity of labour.

Finally, physical resource accuracy across an economy requires incorporation of the energy used in production work (termed exergy), as follows:

$$dY/y = \alpha\left(dK/K\right) + \beta\left(dL/L\right) + \gamma\left(dE/E\right) + \sigma\left(dM/M\right) + \varepsilon\left(dW/W\right) + \zeta\left(dt/t - t_0\right) \tag{10}$$

$\zeta \equiv \left(t - t_0/Y\right)\left(dY/dt\right)$, dY = annual total production (real GDP); dL = annual labour capacity (hours/year), dE = annual energy demand kWh, dM = annual material mass used (kg), dW = annual material mass discharge to environment (kg), α = output elasticity of capital, β = output elasticity of labour, γ = output elasticity of capital, δ = output elasticity of materials, ε = output elasticity of waste discharged.

Limitations

The biological relationships referred to and use in this paper (Section 3.2 and **Appendix**) have evolved from prokaryote species adaptation to their environment over deep time (3.5 billion years). The evolutionary process that has produced them is itself heuristic but those evolved relationships have a fundamental physical basis in thermodynamics. The deep time conservation of the r and K strategies for resource use in biology implies they are fundamental adaptations explored by any production system exposed to limited resources (**Appendix**). Consequently, Equations (7)-(10) should hold true in any model of production applied in a market economy, because in the economy the market plays the role of the environment in biology and ecology.

3. Analyses

3.1. First Generic Systems Behavioural Analysis: The Physical Basis of Economics and Information Utilisation

Economic behaviour is complex and all economic activity is ultimately physical system behaviour. Physical systems analysis has been developed to provide a description of complexity. An apparently simple physical system in an environment that has feedback between the system and environment can show complex behaviour. Systems analysis deals with how complex systems can develop, incorporates the feedback that can lead to chaotic system behaviour and a system following a new trajectory from emergent behaviour beyond a system tipping point.

Paul Krugman has noted that any economy is a complex system within which significant (boom and bust) conditions can emerge and describes the economy as a self-organizing system. The work of Farmer and others has introduced complex system analysis into economics. Macroeconomic analyses need to utilize systems analysis to accurately satisfy Farmer's definition of economic analysis. Setting the physical accounting basis for any economic system starts with defining system boundaries (Figure 2).

For any economic system to physically change, physical work needs to be carried out. Entropy flow impacts on the environment. Pollution arises from dispersal of wastes materials into the environment from a production system (Figure 3).

The Earth as a physical platform for the economy is the source of all the material physical resources that create wealth in the economy (Figure 4). To avoid extinction of life, adaptation to the Earth's environment through natural selection for

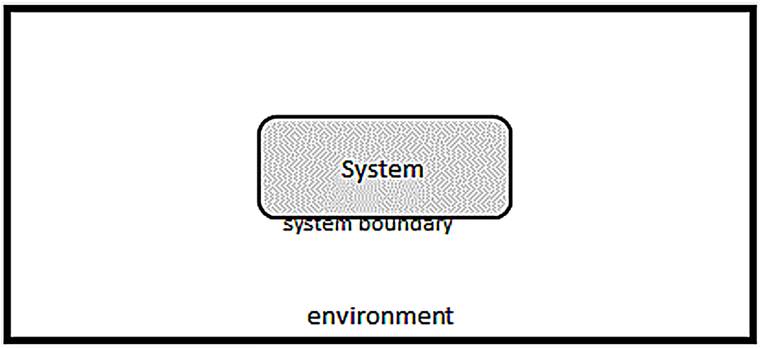


Figure 2. Defining a system. A simple systems diagram showing the system boundary and its location in its environment.

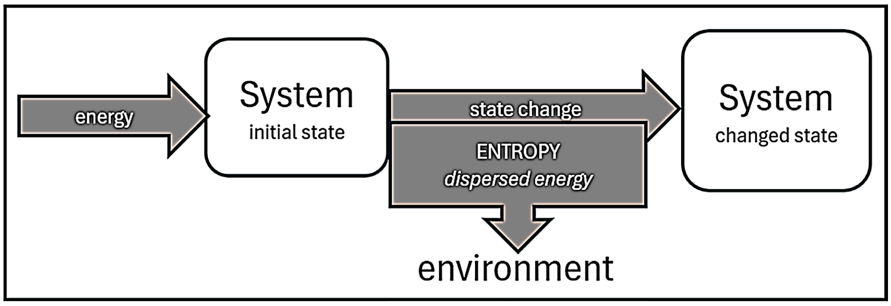


Figure 3. System change process. All production creates entropy and discharges entropy to the environment, in the form of dispersed energy and dispersed materials.

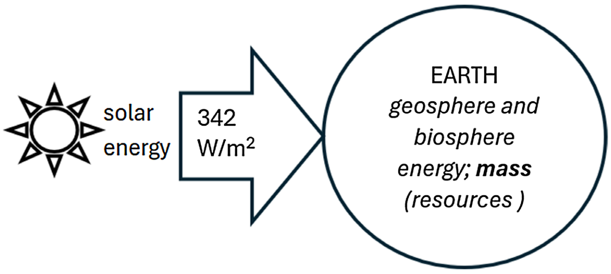


Figure 4. Simplified Earth System Mass and Energy Diagram. The Earth behaves physically as a materially closed system with an ongoing tiny mass loss compared to Earth's total mass from the balance of meteorite and cosmic dust accretion against a slightly larger hydrogen and helium loss to space. In energy terms the Earth is an open system receiving a solar energy input of 342 W/m^2 planetary area. Th evolution of photosynthesis in the most basic independent life forms (prokaryotes including bacteria) has led to the biosphere harnessing that energy to recycle critical resources such as carbon, nitrogen, phosphorus, sulphur, etc., through the biosphere in addition to chemoautotrophic and heterotrophic bioenergy generation and associated material resource exchange. Entropy effects are evident on a planetary level as the dissipation of energy and materials across the biosphere and geosphere. The geosphere provides very long term resource recycling fueled by planetary heat and the biosphere provides short term resource recycling and retrieval of dissipated resources through its biodiversity and ecology.

biological systems has evolved entire ecologies of resource use and resource recycling across the biosphere to avoid entropy accumulating within the biogeosphere to the point at which biodiversity collapses back to its fundamental forms. What is the ultimate natural science describing these critical system behaviors and how they also act within economic systems? Physics, with the most fundamental level of physical system behaviour for use of information originating at the quantum level (Palmer, 2023a).

All production creates entropy and discharges entropy to the environment, in the form of dispersed energy and dispersed materials. The more intensive production becomes, the more intensive the flow of entropy into the environment becomes. The most intensive entropy producer in the Earths biosphere in its history is that presently seen in the form of human economic activity as a linear economy.

To change (state) a quantum system has to redistribute energy between itself and its environment. On a quantum field theory basis, everything is energy—which also means energy is the basis of physical information (Palmer, 2023a). Consequently, Landauer's principle arises—information and its registry (memory)and hence potential use, always has an energy cost.

Quantum thermodynamics deals with how physical systems change through interaction with their environment and the information consequences. These behaviors translate into classical physics and the laws of thermodynamics including:

- the first law of thermodynamics (energy is conserved),
- the second law; any physical system undergoing change has to carry out physical work "W" to change. In the process of change:

$$W - E = T_0 \Delta S_{tot} \tag{11}$$

energy and/or materials are dissipated into the environment surrounding the changing system (where W is the work done when system changes state, E is the total energy, comprising the free energy that contributes to the work done in system change and the final double-term $T_0 \Delta S_{tot}$ represents the energy dissipated into the environment. T_0 is the environmental temperature and ΔS_{tot} is the change in entropy "S") (Palmer, 2019).

All spontaneous (natural) system changes are irreversible. All biological systems and economic systems are open, interacting systems that interact with their environment. For such systems to change and produce anything, they need to consume free energy (the energy available to perform work), to carry out work. The redistribution of energy that occurs in those state changes originates at a microscopic microstate level described by quantum mechanics. At the quantum level, thermodynamic system behaviour has implications for system and state physical information as follows:

$$H = B/T_0 \tag{12}$$

where H = Shannon measure of information (the missing information about the system), B = free energy (exergy) of the system and T_0 is the temperature of the systems environment) (Palmer, 2019; Palmer, 2023a).

The physical reality economic activity is based on emerges from decoherence of the range quantum system energy redistribution probabilities for interaction between quantum systems and their environment. The physical information describing all the resources used in all economic activity, including learning (utilization of information for redevelopment of systems), has a thermodynamic basis (Palmer, 2023a; Palmer, 2023b).

The quantum foundations of systems behaviour in economics are critical to understanding physical production and productivity because they address how production occurs and why thermodynamics places boundaries around physical productivity. Any physical system—any product —has a physical structure whose complexity "is a property of the evolution of a state". The complexity of any physical system is described by its thermodynamic depth (see Lloyd & Pagels, 1988).

Thermodynamic depth is equal to the information designating the development path a physical system has taken to arrive at its present physical form (structure). Consequently the complexity of any physical product is proportional to the difference between the fine-grained information entropy describing its structure and the coarse-grained thermodynamic entropy of the development path of that changed (updated) system. The significance of quantum thermodynamic principles and Lloyds and Pagels work (Lloyd & Pagels, 1988) is that they both demonstrate that the common misrepresentation of entropy as disorder and order is false. Classical thermodynamic entropy is the energy dissipation that occurs during the work done to change the state of a physical system, including production of a product. In terms of physical system information, high entropy relates to low system complexity and low entropy is a property of highly complex systems (Lloyd & Pagels, 1988).

The complexity of any product is therefore a function of the information utilized in its development path. Complex systems including complex products are defined by being low entropy systems. We will now see how this trait of developmental complexity in (re)production is emphasized in biology due to biological systems being learning systems that utilise chemical memory to adapt to their environment (Lloyd & Pagels, 1988). This in turn is the physical system behaviour that also applies to how human knowledge and technology development works in production in the economy.

3.2. Second Generic Systems Behavioural Analysis: Identifying the Origin of Economic Behaviour in Biology

In physical terms, economic behaviour can be reduced to resource acquisition for value creation. Resource acquisition for value creation in terms of re(production) is the physical basis of biology and life and the biosphere and its earliest forms of life provide a 3.5-billion-year record (in genetic code) of testing success in resource acquisition for production (Lane, 2015; Palmer, 2018; Palmer, 2019; Palmer, 2023a).

Prokaryotes have evolved the capability to sense the resource limits of their environment and regulate the expression of their genome within the life cycle of an individual cell towards a social phenotype to maximize species persistence in resource-limited environments. Genes are the agents for intergenerational adaptation but in even the simplest independent forms of life, they encode a capability for sensing resource status of their environment, within an individual cell's life cycle that typically configures genome expression towards social phenotypes in resource limited environments. Information utilization is an integral part of biological reproduction. *Refer to* ***Appendix*** *for the full description of growth and production and evolution of production strategy in prokaryotes*.

In the next section we will see how the creation of surplus resource production by the technology of agriculture created an opportunity to shift human social behaviour to hierarchical society in order to be able to diversify agricultural surplus value into new wealth creation. This was the genesis of the human economy but its resource drivers are purely biological and ecological and shaped by the environment.

3.3. Third Generic Systems Behavioural Analysis: Human Economic Behaviour and Its Origin

Human society is currently understood to have developed from social groups sharing resource acquisition work across hunting and gathering activities. Technology developed for resource acquisition and processing associated with hunting and gathering, including stone tool use and fire is not confined to *Homo sapiens* (Gowlett, 2016). The hunter-gatherer lifestyle extends from the Paleolithic through the Mesolithic to the Neolithic.

Technology, such as shelters/housing emerge as early as the Paleolithic. Division of labour and social complexity are present in hunter-gatherer resource acquisition (Sauvet, 2019) and includes livestock keeping and cultivation consistent with shifting location once resources in an area reduce (Grove, 2009). However, defensible concentrations of resources that can be monopolised are a driver towards institutionalized hierarchy (Smith & Codding, 2021; Woodburn, 1982).

The latter resource management factor (defensible concentrations of resources that can be monopolized) ultimately favours development of fixed-location agriculture even when it is initially associated with reductions in quality of life such as poorer quality diet (Wells & Stock, 2020), less leisure time and reduced resource distribution equitability. The reason for the human persistence with agriculture was the ability it conferred to increase specialization and division of labour by surplus production which could then be concentrated with a social group with a hierarchy that could redistribute surplus production into new specializations—new divisions of labour.

The resource surplus agriculture could provide, combined with increasing specialization thus supported emergence of resource accounting and hence development of writing for information utilization in resource management. Of the species of hominids, *Homo sapiens* appears to be the species with a greater social cohesion that facilitated more effective use of information to maximize returns on resources. The emergence of agriculture in Neolithic as a means to reproducibly generate surplus resources supporting social hierarchies fostering increased division of labour, is the feedback process by which the human economy based on surplus production emerged.

The foundation of primary resource surplus generation in agriculture not only allowed population growth and increased differentiation in labour—it also created a human resource economy that reconfigured the environment as a characteristic of human population development. **Figure 3** (Section 3.1) illustrates why: all production creates an entropy flow into the environment which changes the environment, unless restoration of the environment is undertaken.

The emergence of agriculture in the Neolithic combines configuring the environment through agricultural practice and manipulation of other species (livestock) into human primary resource acquisition that can create a reproducible surplus which in turn can allow a concentration of surplus value, supporting a societal hierarchy that creates new divisions of labour. The consequences of this ongoing process of positive feedback between increasing the efficiency of human information utilization for production, value creation and hence increased resource demand over the last 10 millennia is the human economy displacing other animal resource economies and significantly reducing biodiversity.

Returning to the definition of "Economics = behaviour and accounting" (Farmer, 2024), the positive economic feedback sequence occurring with then emergence of agriculture is relatively obvious from a physical viewpoint. Increasing primary resource surplus supported hierarchical social development, allowing creation of new divisions of labour that broadened the creation of value. This also creates a stimulus for innovation in information utilization as accounting for value now becomes a critical social management factor.

Resource accounting also facilitated the emergence of writing (Kelley et al., 2024). The emergence of numerical accounting and writing in turn created a new basis for information recording and information dissemination that in turn further accelerated specialization in human resource utilization and value creation. These traits are all inherently biological system and ecological system behaviour. The economy is an ecology of physical resources.

The human economy arose from a period in which subsistence level resource acquisition shifted from hunter-gathering with its limits on environmental bearing capacity for the human population, to a mixed model of gathering, animal husbandry and limited agriculture resource acquisition that will have created a need for resource accounting and a system for created value exchange that fed back into development of capability in accounting. The further development of agricultural for surplus production in fixed locations created an opportunity space for the emergence of a less egalitarian and more hierarchical social structures allowing redistribution of surplus value into other services. Some form of social contract for governance of human society emerged with economics.

3.4. Fourth Generic Systems Behavioural Analysis: Use of Information in Production and Its Implications for the Technology Progress Function

Biology is differentiated from physics and chemistry by biological systems utilizing information to adapt to their environment, within the life cycle via sensing and generationally via natural selection, mutation and genetic drift (Lane, 2015; Palmer, 2019; Palmer, 2023b). Resource acquisition is needed to reproduce and survive; surplus resources can be banked (stored) for future use and to diversify value creation and diversification of primary resource value can include creation of public goods. The economy is not new or uniquely human, it's an example of biological resourcing behaviour.

The use of information in economic activity arises from economic activity being fundamentally a biological activity. This is most apparent in the prokaryotes because the over the last 5 decades we have begun to identify how prokaryote genotypes and the information they hold translate into the phenotypes (form and behaviors) of these species. As prokaryotes reproduce as clones, population behaviour for a species arises from genome regulated behaviour and we now know that genome regulated behaviour through chemical sensing within an organisms life cycle can initiate adaptation to environmental change. This use of information in production (growth) is completely transferable to physical production economics as follows.

Second law thermodynamic considerations and Landauer's principle (digital/virtual production) make physical economic production subject to use of energy and materials. *In the human economy, energy is also a critical resource for growth* (Ayres & Warr, 2010; Warr et al., 2010; King, 2016; Palmer & Alford, 2018; King, 2021; Santos et al., 2021; Ayres et al., 2022; Cullen & Cooper, 2022; Ayres, 2023; Jacques et al., 2023), *fulfilling the same role in enabling work*.

From prokaryote growth and its Monod description, we know that the only materials we need to consider in productivity terms are those which are critical resources (r_c)

$$\text{maximum rate of production} = \rho = \rho_{\max} \cdot r_c / k + r_c \tag{13}$$

where ρ is production rate (product/unit time) and ρ max is the maximum possible physical production rate, r_c is the critical resource availability (as energy e.g. kWh and mass e.g. mass of critical limiting material resource(s) (kg/unit time) and k is the production system saturation constant)

The production rate trajectory is a sigmoid curve whose shape is determined by "k". The biological growth analogue again provides the best template for physical production in the economy because it includes consideration of entropy effects on physical productivity:

$$\text{deterioration in production system productivity} = k_d = m \cdot Y_p \tag{14}$$

where k_d is deterioration in production system productivity over time and m is the energy and material input into the maintenance needed to restore production to the maximum product yield per production system ($Y_{p\,max}$).

Consequently, the biological biomass yield relationship (Equation (15) below) provides the most robust physical description of production that incorporates thermodynamic considerations. Hence we can describe mass production maximum product yield per production system for "N" production systems as:

$$\text{product yield per production system} = Y_p = Y_{p\,max}/(1 + m \cdot Y_{p\,max}/\rho) \qquad (15)$$

where Y_p max is the maximum product yield from the production system (usually at startup), Y_p is the product yield during the operating life of the production system, ρ is the production rate (product/unit time) and m is the energy and material input into the maintenance needed to restore production to the maximum product yield per production system) (see **Figure 5**).

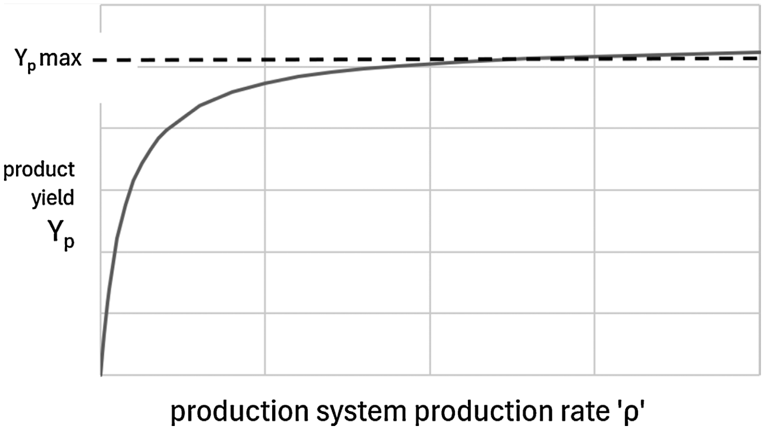


Figure 5. Production entropy effects productivity: there are maintenance requirements to sustain maximum productivity throughout production system operating lifetime both in biological systems (von Stockar, 2013; Palmer, 2023b) and in production in the economy. In both biology and the human economy (Lane, 2015; Palmer, 2019; King, 2016) energy is a critical resource and information utilization is the basis for adaptation to the environment (economically-product creation in the market) and complexity has thermodynamic consequences (Lloyd & Pagels, 1988). Product yield and cumulative production based on a Technical Progress Function for labour in production follows this form of mathematical relationship (Sahal, 1979) which also applies to labour TPF in production which has been attributed to evolutionary development by Sahal (Sahal, 1979) adding to the similarity between economics and biology. Economic production is a complex system behaviour which often displays a power-law relationship which is itself often associated with complex adaptive system behaviour. Another common behaviour with biology is that limits to production can arise from critical resource limitation and production entropy impact on the environment.

We have now arrived at the point where we have a mechanistic physical basis for production that provides a review point for Farmer's recent work applying systems analysis to production (e.g. Farmer, 2024) which adds thermodynamic considerations to it. Farmer investigated the emergence of the production descriptions inherent in Wrights law for mass produced complex mechanical products and Moore's Law for mass produced complex electronic IT products. (Nagy et al., 2013) identified the statistical basis for how technology operates later described in a wider context by Farmer (Farmer, 2024). Their analysis showed how both Wrights law and Moore's Law best describe technological development due to them describing how cost of production drops approximately exponentially with exponential increase in cumulative production.

Farmer (Nagy et al., 2013; Farmer, 2024) describes how the equivalence between Wrights Law and Moore's Law had been previously identified by Sahal. In the publication "A theory of Progress Functions" (Sahal, 1979), Sahal describes how the Wrights law is a form of progress function with wide application due to its consideration of how information is utilized in production.

The Technical Progress Function for total physical production in relation to the information utilization for its development by labour "L" is in the form of a power law relationship:

$$L = a(N \cdot Y_p) - b \tag{16}$$

where Y_p is the product yield from the production system, "a" and "b" are Pareto cumulative distribution function constants stem, ρ is the production rate (product/unit time) and m is the energy and material input into the maintenance needed to restore production to the maximum product yield per production system.

Sahal identifies the mathematical form of a labour Technical Progress Function (TFP) as a Pareto power-law (Sahal, 1979). Sahal states in a footnote to his 1979 paper "*To the best of my knowledge, no other study has obtained such an explanation of the Pareto distribution in terms of certain invariant characteristics of evolutionary systems*" (my italics).

The independent analysis undertaken in this paper can identify Sahal's universal progress function in the form of a power-law relationship arising from information utilization in any production being a complex adaptive process, in the same way that information use in biological adaptation is.

In the human economy the market plays the role of the environment and knowledge acquisition and its utilization is the principal economic input from labour (in comparison to direct physical work done by labour). Information acquisition (knowledge development in education) and knowledge creation (innovation through research and development) is the basis for technology creation and diversification of value creation. Information utilization in the economy is bounded by thermodynamic rules. For example, Equation (2) cited previously ($H = B/T_o$) is profound: it implies that all change is relative. It also implies that changing any system, that producing anything, requires physical work to change the system information.

4. Thermodynamics and Information

Lloyd and Pagels (Lloyd & Pagels, 1988) provided the first physical (thermodynamic) definition of complexity. The complexity (thermodynamic depth of any physical system such as a product, $\mathcal{D}_r$, is proportional to the difference between the coarse grained entropy $\bar{S}$ of the system (its thermodynamic entropy) and the fine-grained entropy, so which describes its development path into that state:

$$\mathcal{D}_r = \bar{S} - S_0 \tag{17}$$

In economic terms: all production requires physical work (which produces entropy); all products have physical information that defines them and production of a product is the outcome of use of information to create the product from its material inputs.

This has profound consequences for technology development in an economic context. The information required to produce any product is a combination of the information required to facilitate the manufacture of the product and the information utilization in its production. As products become more complex i.e. have greater thermodynamic depth, they require an increasing amount of labour time and expertise to produce.

The knowledge a unit of labour uses in production is enabled by the individuals total education time plus the laborer's time input into the production process. This process of information utilization in an advanced economy also includes the time of all the laborer's contributing to development of a competitive price for the product by developing the systems for its mass production and all the information needed to extract and prepare the products raw materials to the point they can be assembled into it.

The greater the complexity of a product, the greater and more intense the information utilization is in bringing it to the status of a competitive product from an adaptable producer acting in the competition-space that is any economic market. For complex adaptive systems a commonly observed distribution of behaviour is often some form of power-law relationship.

The emergence of power-laws from analysis of productivity and value distribution in itself does not provide a specific mechanism for economic production but this paper has now presented the link between Sahal's identification of a Pareto form for Technical Progress Function and physical system behaviour.

The Pareto form of a Technical Progress Function arises endogenously from how information utilization feeds into production system adaptation and technology evolution. A complete (i.e. endogenous) explanation for how production works physically is provided by descriptions of production already existing within biology—as described above.

4.1. Using Technical Progress Function (TPF) and Total Factor Productivity (TFP) in Macroeconomic Growth Analysis and Projection

To provide an accurate macroeconomic growth description for an advanced (mechanized) economy, both energy use (Ayres & Warr, 2010; Warr et al., 2010; Palmer & Alford, 2018; King, 2021; Ayres et al., 2022) and information use (King, 2016; Palmer & Alford, 2018) by labor need to be accounted for in accounting for the function of technology. For example, only if the Solow macroeconomic growth description (Solow, 1956; Solow, 1957) includes energy (as free energy, a.k.a exergy) use *does it close its Total Factor Productivity gap to real data* (Ayres & Warr, 2010; Warr et al., 2010; King, 2016; Palmer & Alford, 2018; King, 2021; Santos et al., 2021; Ayres et al., 2022; Cullen & Cooper, 2022; Ayres, 2023; Jacques et al., 2023). A complete description of the relationship between production and growth also requires an accurate Technical Progress Function to describe *how* labor uses information to produce in thermodynamic terms. Accurate growth forecasting should not involve using *either* Technical Progress Function (TPF) *or* Total Factor Productivity (TFP) in economic analyses of production. My analysis of the physical basis of production shows that TFP and TPF provide different information and both are needed in growth analysis if they can be correctly defined (Sahal, 1979; Nagy et al., 2013; Paniccià et al., 2013; Santos et al., 2021). The analysis in this paper also implies that one is an essential part of the other (a correctly defined TFP e.g. Equation (10) would be part of a full TPF. If either of them is incorrectly i.e. subjectively defined (and lacking thermodynamic considerations), both can be a source of misinformation in economic assessments.

The most physically coherent form of Technical Progress Function (TPF) available is Sahal's TPF (Sahal, 1979) as defined in Equation (10) above. Sahal's TPF is one that can accommodate thermodynamic considerations for how information is used by labour (L) in production. The TPF provides understanding of the diminishing returns on information use by labour in production which are necessary to both appreciate the risk of secular stagnation and appreciate the value of strategic investment in education and long term strategic research and development in an economy.

In contrast, Total Factor Productivity and its use in macroeconomic growth analysis needs to take into account the implications of Sahal's Technical Progress Function and the role of product complexity and thermodynamic depth in that. In addition to making that provision for the productivity contribution of labour, a viable and objective Total Factor Productivity also needs to acknowledge the thermodynamic significance of energy and free energy (exergy) in particular, in providing a TFP otherwise the TFP an economist develops will be subject to the same inability to match data that was true for the Solow residual in application to actual data for macroeconomic growth (Palmer & Alford, 2018).

Without incorporation of thermodynamic terms, Total Factor Productivity (TFP) is the outcome of production work done arising from production information utilization efficiency and the number and efficiency of production assets (the latter explaining why growth does show a dependence on investment in production (e.g. Bernanke & Gürkaynak, 2001).

The Solow residual is in fact entirely viable in deriving Total Factor Productivity *if thermodynamic considerations are built into it* (Palmer & Alford, 2018; Santos et al., 2021; Ayres et al., 2022; Cullen & Cooper, 2022; Ayres, 2023; Jacques et al., 2023). It has been used as such for an examination of global economic growth (Palmer & Alford, 2018). The following approach shows how.

There are two principal characteristics that need introducing into a Swan-Solow macroeconomic growth description to render it physically accurate:

(i) consumption of free energy (exergy) (Ayres & Warr, 2010; Warr et al., 2010; Paniccià et al., 2013; King, 2016; Palmer & Alford, 2018; King, 2021; Santos et al., 2021; Ayres et al., 2022; Cullen & Cooper, 2022; Ayres, 2023; Jacques et al., 2023).

(ii) the role of information utilization in production (Palmer & Alford, 2018).

Information utilization in the development of and optimisation of a product/service, towards maximising its fitness to secure market share and return value in the market (product environment), is endogenous to human productivity. It works in the same way information utilization does in all biological systems.

A physical basis for uprating the Swan-Solow macroeconomic growth formula can be developed as follows (Palmer & Alford, 2018):

$$Y(t) = \text{Total Production (GDP) for year } t;\ K(t)\alpha(A(t)L(t)(1-\alpha) \tag{18}$$

where $Y(t)$ = Total Production (GDP) for year t; $K(t)$ = capital for year t, $L(t)$ = labour capacity for year t, $A(t)$ = technology productivity factor for year t and α = elasticity of output with respect to capital (Palmer & Alford, 2018).

This formula can be updated from its Mankiw, Romer and Weil revision which includes human capital, to incorporate Cobb-Douglas production functions as follows

$$Y = AL\beta K\alpha \tag{19}$$

where Y = annual Total Production (real GDP); K = annual capital input, L = annual labour capacity (hours) year t, A = Total Factor Productivity (TFP), α = output elasticity of capital and β = output elasticity of labour (Palmer & Alford, 2018) such that the macroeconomic growth description becomes:

$$dY/y = \alpha(dK/K) + (\beta dL/L) + \gamma(dE/E) + \sigma(dM/M) + \varepsilon(dW/W) + \zeta(dt/t - t_0) \tag{20}$$

where $\zeta \equiv (t - t_0/Y)\ (dY/dt)$ and where dY = annual total production (real GDP); dL = annual labour capacity (hours/year), dE = annual energy demand kWh, dM = annual material mass used (kg), dW = annual material mass discharge to environment (kg), α = output elasticity of capital, β = output elasticity of labour, γ = output elasticity of capital, δ = output elasticity of materials, ε = output elasticity of waste discharged (Palmer & Alford, 2018).

A Swan-Solow-Mankiw (or similar) macroeconomic growth model can accurately model growth if it includes a thermodynamic basis for TFP that includes exergy and preferably also provides a reference to information utilization, the efficiency of information utilization and its outcome as technology development.

4.2. TPF and the Consequences of Product Complexity (Product Thermodynamic Depth)

The use of information by labour in research development, innovation and development of products and development of mass production is bounded by simple physical resource limits when relating productivity to resource acquisition. Information utilization in the economy operates to the same thermodynamic constraints it does in biology. Adaptation emerges from complex systems using information feedback (Holland, 1996; Holland, 1998). Biological species groups (taxa) follow a power-law relationship in the number of species in taxa for which the underlying mechanisms include resource competition, spatial separation of species populations and genetic drift (Newman, 2005). Extreme physical information such as that associated with biological systems follows power-laws, arising from the systems' complexity (Frieden & Gatenby, 2005). Power-laws are also associated with scaling in ecological systems (Marquet et al., 2005). Power laws are also associated with biological phenotype fitness landscapes which can predict adaptation rates.

Technology is simply the application of utilization of information (knowledge) to the acquisition of resources for production. Technology is also a process. Technology relies on research and development to generate new objective knowledge (generally from scientific advances) that feeds into new product creation and development and additional information in the education system that provides labour with its information utilization capability.

In general, as more objective knowledge is accrued, product complexity increases;

- as product complexity increases, the thermodynamic depth of products increases,
- as product and production process thermodynamic depth increases, the work needed to produce a product increases and the entropy of product production increases.

This trend is demonstrated in biology and the history of Earth's biosphere and its increasing complexity of organisms that genome development for resource leverage has produced. It can also be demonstrated by analysing the time labour takes to create and mass produce a new product, as follows.

I will now provide two case studies to illustrate the impact of product complexity, referencing examples of production of a product with the same fundamental utility at very different levels of technology. A common baseline on product use can be provided by ensuring provision of similar utility in different technology environments. To provide a common underlying (fundamental) utility basis for this analysis I will look at two critical and universal human utilities—one based on energy (personal heating) and one based on communication (long distance communication).

For heating, two extremes we can consider are the earliest form of heating from fire in the form of a campfire and compare it to technology development a far more complex mass heat generation and broader energy provision in the form of a nuclear power station.

An open fire of 0.5 kW heating for 7 people provided by wood friction (bow drill) usually requires 112 hours for a user to learn the skills to provide and conservatively assuming 1 hour for identification of appropriate wood for fuel, 0.5 kW of heating by open fire takes 113hours of Labour time to serve 7 people = 113/7 = 16.1 hours Labour time in information utilization/person heated.

Years of scientific research enabled the development of nuclear fission—40 years. In addition, the provision of a single nuclear power station, typically of 1 GW energy generating capacity, requires a highly skilled design team of 100 specialists, a construction team typically around 8000 and an operational team of 700. The combined information utilization capability of all Labor sums as 1.25 billion hours based on standard assumptions for a facility providing on average 38.9 kW/h/day to each household served. The power station provides an extended utility in providing electricity that can service all household electricity needs in addition to electricity use for personal heating. This equates on average to 16.48 kWh/day electricity to each person served, of which the typical personal usage is 0.5(3) kW per person. A 1 GW nuclear power facility serves heating to 1329053.7 people on this basis:

The Labour time in information utilization/person heated = 1.25 billion hours information acquisition and utilization/1329053.7 = 945.6 hours/person served.

➢ The more complex technology takes 945.6/16.1 = 58.7 times more labour information-time per person served to provide 0.5 kW of personal heating based on multiple specializations in labour (compared to baseline level capability in the case of fire)

For long distance communication we can consider two technologies much closer in time in terms of their emergence: the original Bell telephone and the extended utility Smartphone, stopping at the 5th generation. Based on the crude assumption that a development year is full time for both technologies;

1) Bell telephone (principal utility—long distance communication)

Concept research—harmonic telegraph—1873-74
demand assessment (market research)
concept development—1874
pilot/prototype production: June 1875
legal-patenting: patented 14th Feb 1876 (US patent)
development of mass production capability
mass production: 1877 (Bell Telephone Company established)

Using face value product development time only: Total time = 1873 to 1877 = 4.5 years = 1461 days = 39,447 hours product development time involving small development team to market

2) SMART phone development via cell phone (principal utility—long distance communication)

Concept research: first cell phone—10 years (from 1973 to market 1983)
demand assessment (market research) (included in above)
concept development (included in above)
pilot/prototype production (included in above)
legal-patenting: (included in above)
development of mass production capability (included in above)

Development of smart phone from cell phone (1994) mass production (IBM Simon prototype to market in 2 years)

demand assessment (market research) (included in above)
concept development (included in above)
pilot/prototype production (included in above)
legal-patenting: (included in above)
development of mass production capability (included in above)

Development of smart phones with multiple utilities from first smart phone

advanced capability smartphones (average 2 - 3 years to develop for each generation of Smartphone—2.5 per generation assumed))

pilot/prototypes production (included in above)

development of mass production capability

mass production

Total time for first generation smartphone = 10 + 2 + 2.5 = 14.5 years = 5296 days = 127,107 hours product development time

Using face value product development time only: Total time for current 5th generation smartphone to market from first cellphone = 10 + 2 + (2.5 × 5) = 24.5 years = 8948 days = 214,752 hours product development time (thousands of developers)

➢ The more complex long-distance communication technology with expanded utility took 5.4 times more development information-time to market supply than the Bell telephone.

The references for these two thermodynamic depth impact case studies are:

- https://en.wikipedia.org/wiki/History_of_mobile_phones-:~:text=Advances%20in%20mobile%20telephony%20can,5G%20began%20deployment%20in%202019
- https://www.thalesgroup.com/en/markets/digital-identity-and-security/inspired/basics-of-mobile-networking/milestones
- https://www.telefonica.com/en/communication-room/blog/first-smartphone/
- https://en.wikipedia.org/wiki/Smartphone
- https://www.weforum.org/stories/2018/03/remembering-first-smartphone-simon-ibm/
- https://heritagecalling.com/2022/07/29/the-story-behind-the-worlds-first-telephone/
- https://www.sciencemuseum.org.uk/objects-and-stories/ahoy-alexander-graham-bell-and-first-telephone-call

I have now shown the physical (thermodynamic) basis for the success of the division of labor. Human labor has an economically deployable sustainable information utilization capacity based on the information utilization capability conferred on an individual from life-experience and objective teaching (education). The fundamental basis for the creation and expansion of objective (as opposed to subjective information (misinformation) in an economic environment is science and scientific progress. The same information utilization process applies in nature, where species diversification represents a range of information used towards adaptation to optimizing returns on resources. Advances in technology development fundamentally depend on scientific capability and capacity, not mass -processing of information. Consequently, as an economy diversifies its products, partly competing on the basis of thermodynamic depth (complexity), increasing product complexity translates into a need for labour to acquire a thermodynamically deeper economically deployable sustainable information utilization capacity—labor needs a deeper education to service the information demand profile of a diversifying and continuously adapting market.

There is maximum sustainable information utilization capacity from labor which becomes more productive when the information capacity and capability is narrowed and deepened into information specialization (Smith's divisions of labour).

The long-term consequences for a materially closed system of increasing product complexity and the associated increase in product thermodynamic depth is that there are diminishing returns from the use of labor in information utilization for product creation and development (Bloom et al., 2020). That is now beginning to emerge in advanced mechanized economies as secular stagnation.

All production requires physical work and all production generates an entropy flow into the environment from production. Understanding how information utilization drives biological adaptation to the environment also provides us with insight into how technology works in the economy.

4.3. Production Entropy across the Global Economy

The other physical drivers of diminishing returns on production which drive secular stagnation are:

- mechanized production and increased product complexity increasing the environmental entropy associated with products (increasing the on-cost of production and diminishing the natural capital available to the economy),
- fossil fuel entropy and its inflationary impact through climate change on all energy use in mechanized production increase the natural capital debt of the economy.

Figure 6 illustrates the principal resource and entropy flows of production into the global environment from the economy.

A solution to the thermodynamic depth driver of what is currently described as secular stagnation, would be for governments to invest more into fundamental scientific research and development of A.I. in support of it. The analysis undertaken in this paper implies that the fundamental innovation driver across the economy is provided by advances in fundamental scientific knowledge. That cannot be provided by AI alone; AI can only augment and facilitate it.

4.4. Costs of Production Entropy in the Global Economy: Analysis of Productivity in a Service Industry Required for the Mitigation of Production Entropy in Order to Sustain the Global Economy

I will now use a case study of the water industry to investigate its productivity in comparison to Sahal's power law basis for his progress function. This paper examines the impact of global economic production entropy on growth and oncosts usually unaccounted due to them being designated externalities. The principle of the physical global system analysis is that all factors are endogenous to the system. In that context the water industry is of interest because its function is to

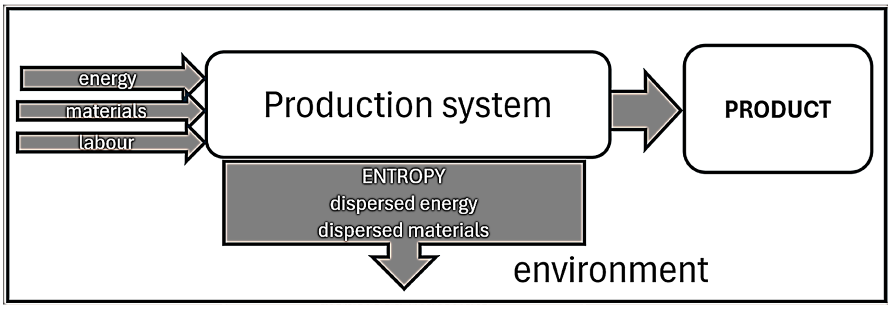


Figure 6. Universal Production System Diagram. All production creates entropy and production systems all discharge entropy to the environment, in the form of dispersed energy and dispersed materials. The higher the entropy flows to the environment, the greater the risk of habitat change and habitat loss. Habitat change and loss lead to species extinction for species unable to adapt to the rate and extent of change occurring in the environment. That represents a loss of evolved information from the Earth that contributes to the Earth's physical resource economy efficiency. The loss of ecological niche organisms that contribute to the most rapid part of Earths resource recycling efficiency (biological recycling, as compared to geochemical recycling) reduces the overall efficiency of planetary recycling leading to an increased rate of entropy accumulation in the environment. As entropy represents energy and physical resource dispersal, the costs of raw material acquisition for use in the economy increase over time.

manage the impact of human population and its economic activity on the aquatic environment.

The water industry serves both a public health role and an environmental protection role to a level of basic need that has kept the bulk of its service provision in the role of strategic public service on a global, basis.

Wastewater treatment processes wastewater from individual households, commerce and industry to produce a discharge meeting quality standards set by an environmental regulator, in reference to the needs of the local environment.

In England and Wales, the privatized water service is also commercially regulated by a commercial regulator, OFWAT. OFWAT maintains records and metrics of water utility assets obtained from the utilities. In wastewater treatment, it has set six size categories for treatment in terms of the population served by a treatment plant for comparison of utility operations.

The operational and hence technological minimum capability of the treatment system is set by the requirements of the environmental discharge permit, whose provisions should not be exceeded.

Quality permit non-compliance can lead to court cases and imposition of fines. The operational capacity of any local treatment system is determined by the population (Population Equivalent, PE) of the wastewater catchment area including allowances for commerce, tourism and permitted industrial discharges. Treatment capacity and capability is designed to these criteria with allowances for future increases in population served during the working life of the treatment plant.

In the UK and globally, technologies deployed for wastewater treatment are designed for robustness (civil engineering assets have a nominal 60-year life) and typically deploy treatment processes relying on solids sedimentation and biological treatment as these offer the lowest cost per volume of water processed for high masses and volumes (Table 1).

Table 1. OFWAT size categories for U.K. wastewater treatment works.

OFWAT Category Size	PE Served
6	>25,000
5	10,000 to 25,000
4	2000 to 10,000
3	500 to 2000
2	250 to 500
1	0 to 250

The OFWAT Wastewater Treatment Works (WwTW) size categories are based on equivalent population (PE) served, for the treatment capacity needed to treat combined domestic, industrial and commercial wastewater.

Treatment costs include power for pumping and aerobic biotreatment aeration, chemicals, specialized labour, materials, treatment of treatment system residual materials and bulk transport amongst a range of other lesser costs.

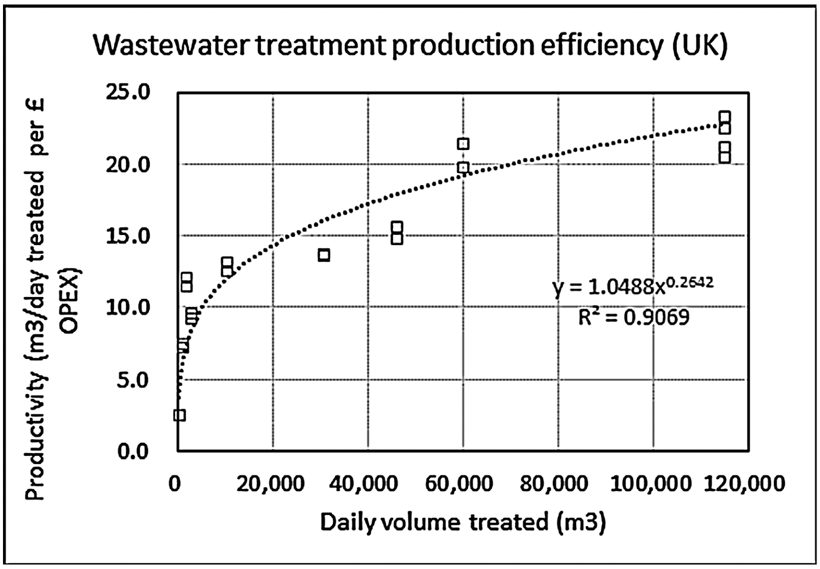
After meeting the overall treatment requirements, including residuals treatment, water utilities can also choose to invest in technologies that increase their treatment efficiency. That can include recovery of renewable energy from residuals treatment or other energy recovery or even some material recovery. Wastewater treatment processes have to treat huge masses and volumes of water so they have a significant operational energy demand.

Renewable energy recovery systems can reduce operational carbon emissions linked to fossil fueled energy, by the treatment works using generated renewable energy to reduce overall internal power demand.

Alternatively renewable energy generated can be sold on the external market, generating a revenue stream to offset total cost of treatment.

Observation of a power-law relationship is service productivity such as that seen for the UK water industry in Figure 7 (above) should not automatically lead to an assumption that efficiency follows a power-law relationship originating in the role of rises from information utilization in production by labour. In the water industry the size of the wastewater treatment plants follows the size of the communities they serve (population agglomerations). Population agglomerations are known to follow a power-law distribution (Newman, 2005), so population agglomeration data is a driver for power law distribution emergence in analyses of water industry asset base productivity.

The purpose of the water industry is to preserve the quality of a non-substitutable critical resource (water) such that it is fit for human consumption and is present in sufficient volume to service the human population demand and the demand of the economy, while also mitigating production entropy impact on



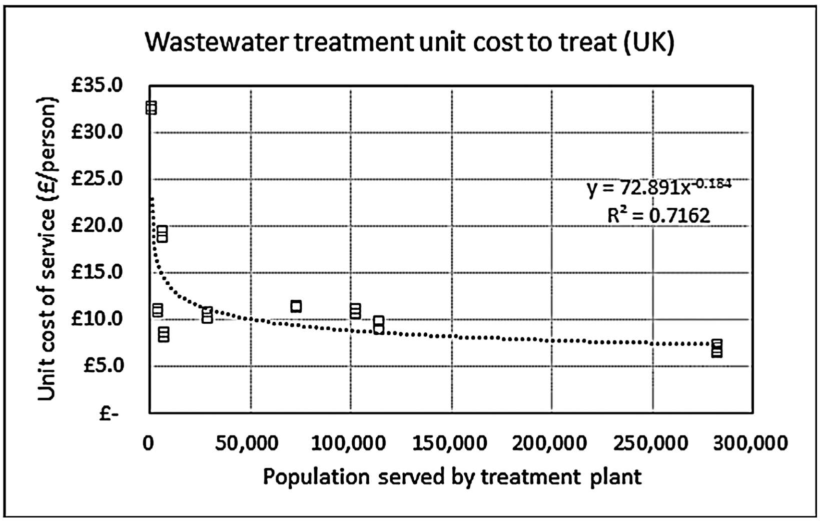


Figure 7. Power-law relationships in water sector production: wastewater treatment case study. Both graphs show the wastewater treatment key production relationships for the full range of OFWAT treatment capacities populations served) for a range of different permit (quality) requirements. The upper graph shows the best fit relationship for treatment work productivity and output is a power-law relationship. The lower graph shows the best fit relationship between unit cost of service (£/PE served) and installed service capacity (PE served) for a range of different discharge permits, which is also a power-law. The lower graph describes a profile often associated with power-law relationships. It also describes a significant Pareto efficiency in wastewater treatment economics: less than 20% of the treatment works (by number) carry out more than 80% of overall treatment work across a utility. Those works are the largest in a utility wastewater asset base. Economies of scale occur in production (shown as specific volume of wastewater treated in the left hand side graph). Treatment works serving larger populations have larger load impacts on the environment and consequently often have higher discharge quality requirements for human pollution parameters than small works. The labour requirements for treatment are higher for small works than large due to the concentration of pollution load in one place at large treatment works. Treatment technology overall efficiency increases with scale of treatment (upper graph) and this translates into both specific capital cost and specific operational cost (lower graph) also following a power law relationship.

receiving waters to protect human health and to minimize the degradation of aquatic habitats in order to preserve their biodiversity. The effect of production entropy and only part of the cost within the global economy needed to reduce it can be seen in the water industry.

The treatment works with the lowest cost to serve of all treatment works in the whole wastewater asset base are those that have the largest economy of scale (large works) which also practice circular economy resource efficiency—they have facilities for converting treatment residual waste into renewable energy which significantly reduces their cost to serve even compared to assets of the same size that lack this greater resource-efficiency capability.

Case study on missing information in current policymaking: the global water industry is an example of an oncost to the global economy arising from the pollution part of global production entropy which also contributes to sustaining the global economy. A physically based analysis of its strategic value identifies this broader strategic value by considering entropy of production but current neoclassical analysis overlooks this fact due to its lack of physical definition and hence underestimates the strategic value.

5. Analysing Supply, Demand and the Effect of Entropy on Value in the Global Economy Viewed as a Physical Resource Ecology

The physical implications of the global economy being bounded by thermodynamic laws for energy, production work and the impact of production entropy are that its range of resource acquisition behaviors are similar to those which emerged in biology in Earth's biosphere. In the biosphere individual organism production for species which are independent forms of life (i.e. excluding virus) to increase the population of the species to occupy space and secure resources within its environment, is a dynamic, adaptive process that uses genetic information between generations and sensing of the environment within an individual organism's lifetime. The process is information dependent and objective-information driven; misinformation or disinformation is not tolerated in natural selection. Information used for adaptation needs to properly represent the state of the environment.

The process is also dynamic because a biological resource ecology can change its environment while it is seeking to adapt and maximise its resource acquisition for reproduction from it. The human economy reproduces this behaviour with the market representing the environment. The U.K. and its economy can be referred to as an example of how information use in knowledge development supporting technology development can in turn re-shape the market.

The development of the economy in the U.K. (**Figure 8**, upper graph below) provides an illustration of how information utilization drives technology which in turn drives development of new products of increasing complexity in an advanced economy. From the introduction of agriculture and its surplus primary level production the level of GDP per capita for the UK population was relatively static until advances in information utilization led to mechanized production, which resulted in the total work and production capacity in the economy increasing steeply. The reason for this was that mechanization exponentially increased GDP per capita which fed back into rapidly increased value for the entire UK economy. Social contract interventions by government into education and health including water treatment in particular, fed back into increased innovation and increasing population.

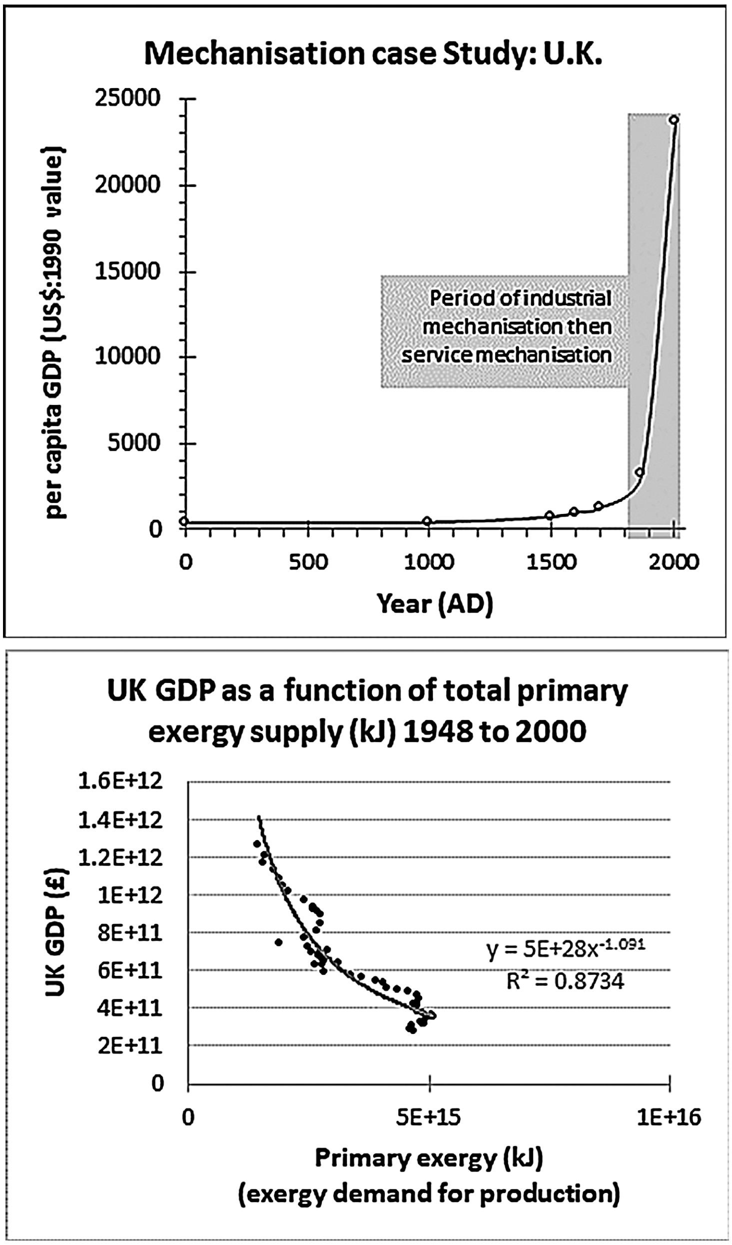


Figure 8. The evolution of an advanced economy. In this case the U.K. provides a case study for how information utilisation efficiency (knowledge and technology development) feed back into increased per capita productivity and value creation arising from mechanisation.

The physical factor that dominates Total Factor Productivity (TFP) is free energy (also known as exergy) because in the energy supplied to do work it is the free energy that does work while part of the total energy supplied to do work is dissipated into the environment work. Consequently energy (exergy) is the most critical resource in an advanced economy where labour high productivity is provided by mechanization. By applying exergy analysis (accounting for the free energy available to do production work) to technology factors including TFP, neoclassical macroeconomic growth can fit to long-term historic economic data for the UK (Warr et al., 2010). The previous analyses of TFP and TPF described in this paper give an explanation for why the lower exergy graph in **Figure 8** displays a possible power—law relationship for UK GDP and UK exergy demand.

Once the UK economy had transitioned to an advanced (mechanized) economy, the principal physical determinant of growth became exergy supply for production.

The UK case study in **Figure 8** which applies to all economies transitioning to mechanization leads to consideration of two other significant outcomes of the thermodynamics of production on a global basis.

The derivation of a TFP such as a Solow residual (Solow, 1956; Solow, 1957; Paniccià et al., 2013) without physical determinants leads to erroneous outcomes. For example, use of a non-physical Solow TFP led Solow to conclude that long-run growth is exogenous. This is wrong (Bernanke & Gürkaynak, 2001) and results from the missing information (physical information) in the form of the original incomplete Solow residual. The dominance of TFP by exergy which has now been established (Ayres & Warr, 2010; Warr et al., 2010; King, 2016; Palmer & Alford, 2018; King, 2021; Santos et al., 2021; Ayres et al., 2022; Cullen & Cooper, 2022; Ayres, 2023; Jacques et al., 2023) and all energy use has an associated entropy impact. As UK energy supply for GDP for the period shown in **Figure 8** below was dominated by fossil fuels, GHG emissions in terms of carbon dioxide equivalents (CO_2e) also increased exponentially until government intervention in transitioning fuel use for energy production from fossil fuels to renewable fuels.

Climate change is the most immediate example of an accumulating natural capital debt for the global economy from production entropy due to insufficient current investment in a more immediate transition to non-fossil fuels. Analyses of this problem using carefully built aggregate models such as the Nordhaus DICE (Nordhaus, 2017) which is widely used for climate policymaking still suffer from missing information—the forms of physical information described in this paper. The consequence is that reading DICE as a recommendation for limiting the urgency of global spend on the transition from fossil fuels is an underestimate of the cost of shifting spending to later adaptation because the fuller entropy considerations are missing from the DICE analysis.

The dependency of advanced (mechanised) economies such as that of the G20 for example, on energy supply renders them increasingly vulnerable to energy supply shocks (see **Figure 9** below).

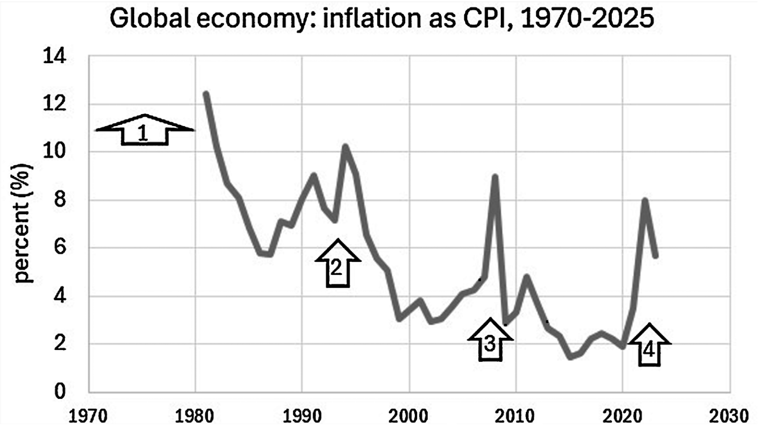


Figure 9. Vulnerability of mechanised global production to physical (energy resource) supply and demand risks 1970-2025. Inflation has significantly peaked in the global economy on four occasions in the last 5 decades. From 1970 to 1980 (1) and in 1990-95 (2), fossil fuel supply shocks and rising fossil fuel prices led to fiscal crises that were associated with spiked global inflation. In contrast, in 2008 (3) and 2020 (4-COVID-19) fiscal crises led to energy supply disruptions that combined to significantly increase global inflation.

5.1. Production Entropy and Long-Term Inflation

For short term inflation (short term degradation in the value-potential of the economy), existing economics provides sufficient explanation for how management of the medium of value exchange (money)creates inflationary or deflationary outcomes in the market.

In comparison, long term market inflation and long-term currency devaluation trends follow more gradual change and are driven by a physical quantity – the entropy of the global economy. Entropy-driven long-term inflation currently has a consistent downward (devaluing) trajectory, with the underlying mechanism being the aggregate effects on global production costs of global production entropy and how it continues to accumulate in a semi-closed system. The direct entropy of production is the main driver of this long-term value erosion but there is also a role played by the complexity of global products in an advanced global economy. The more complex a product is, the more information utilisation work (knowledge acquisition and its use) is needed to produce an enhanced utility product leading to observations of diminution in returns on knowledge (Bloom et al., 2020). Consequently, it takes more work to produce complex products including the successful engineering of their mass production, than it does to produce a product of low thermodynamic depth.

The elements of production entropy that contribute to increasing costs of production (Faber et al., 1995; Bakshi et al., 2011; Henckens et al., 2016) and long-term inflation include:

- dispersion of material resources across the biogeosphere which results in their re-use requiring more work and hence cost use in future;
- substitution of substitutable resources: the market selects resources based on their cost with preference for the lowest cost, so sequential consumption of

substitutable resources increases cost over the long term. The classic example of this is decreasing Energy Return on Investment (EROI) for fossil fuels.

- the criticality of energy demand in mechanised (advanced) production and its role in the global economy amplifies the effect of diminishing fossil fuel EROI
- the accumulation of dispersed wastes from production into the environment (atmosphere, water and terrestrial) and any costs to human health or natural capital that result from that accumulation (Nordhaus, 2017).

Supply and demand inefficiencies are both endogenous risks in a physical model of the global economy. The success of management interventions by government depends on the cause of an economic crisis be accurately identified as a supply or demand problem on a physical basis and also depends on the remedial measure(s) applied having a demonstrable (analysis supported) physical mechanism for success.

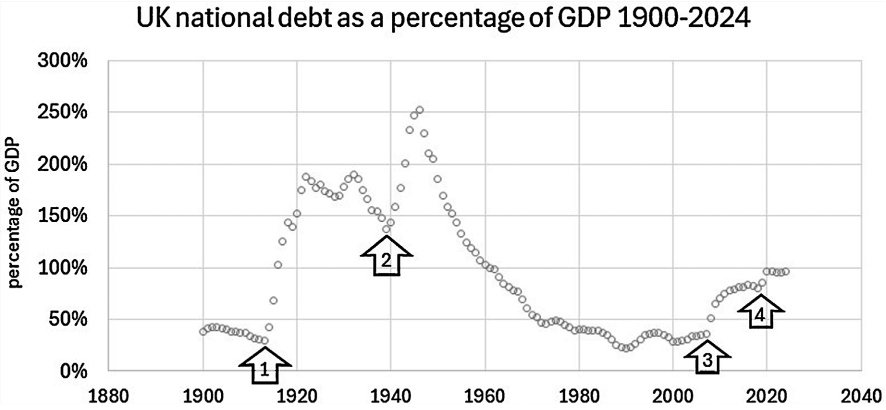


Figure 10. UK governance and management of its money supply reflects government perception of its role in managing its social contract with the nations its represents. For example, threats seen as existential national threats resulted in use of national debt to address such problems (1= World War 1; 2 = World War 2, 3= global banking crisis of 2008, 4 = COVID-19 pandemic. There is an emerging existential risk to the UK and the global economy which has not yet triggered this degree of intervention but is likely to: global climate change.

If the original basis for acceptance of a social contract based on reducing equality and introducing a hierarchy sufficient to manage the redistribution of the common wealth such that surplus production could be translated into diversification of labour which then expanded the human economy, the emergence of a medium of exchange(money) was only a tool for facilitating diversification of the human economy. That principle is considered at government policy-setting levels leading to higher tolerance of social (e.g. national) debt at times of severe crisis (e.g. **Figure 10** above).

Physical analysis also provides us with the benefit of a clear identification of the status of facets of economic accounting based on natural science cause and effect. For example, all the physical factors of production are endogenous—the thermodynamic systems analysis identifies the fundamental mechanisms driving all of them. None of the elements of production that need to be accounted for lack a thermodynamic system explanation, as demonstrated by reference to how they act in the resource economy of Earth's biosphere.

The benefits of creating a physical foundation for economic analysis include us now being able to discern physical mechanisms in resource acquisition and global production for secular stagnation. Not doing so leads to profound information gaps in accounting for production potential and economic growth, including:

- the global economy consequences material boundaries of the Earth.
- the effect of production entropy on the natural capital of earth and the work needed to extract its resources for use and in an advanced economy with increasingly complex products.
- the increasing work input required in research and development to bring innovative products to market.

The global market as a physical resource ecology is physically bounded system driven by physical behaviours, within which biology is the platform for the adaptive (innovative) work that information utilization provides. There are identifiable factors by which the entropy of global production translates into long-term inflation in the global economy:

- resource depletion and substitution of depleted resources (Faber et al., 1995; Bakshi et al., 2011; Henckens et al., 2016).
- value and cost of critical resources that cannot be substituted as demand for them increases (those essential to work and innovation; including resources like water, phosphorus etc., objective information acquisition and energy availability in a mechanized economy) (Faber et al., 1995; Bakshi et al., 2011; Henckens et al., 2016).
- degradation of the wealth potential in the biosphere from production entropy flux into the environment (Faber et al., 1995; Bakshi et al., 2011).

Supply and demand are both endogenous elements of a physical resource economy that operates through a credit and value exchange system for resource acquisition. Human behaviour in information utilization in market decision-making has emerged relatively recently from psychology research including prospect theory (Kahneman & Tversky, 1979). The basis of for resource choice in the market is hence asymmetric and skewed against loss (loss aversion)—expected utility theory of rational agency is a false premise and does not apply in the real market (Kahneman & Tversky, 1979; Kahneman, 2011).

Physical analysis we are now capable of now even extends to being able to replace market equilibrium theory. A physically base simplified assumption for supply and demand transactions in the market is to assume they represent a stochastic range (distribution) of need for the product and its utility for a given price overlaid by the range (distribution) of supplier price acceptability. The expected outcome of exchange of information across the market would be that the intersection of most probable purchase price and most probable sales price gives the same outcome as the classical supply-demand curve identification of the most probable market price. The supply-demand intersection still identifies price but there is not equilibrium involved—its occurs at the intersection of most probable selling price and buying price for all the participants in the market (Komlos, 2022). No market equilibrium and equilibrium theory is required. The supply-demand curve crossing point can be described as a stochastic outcome of market information exchange.

Information is rarely if ever complete so perception plays a significant role in taking action and in biases such as loss aversion being triggered. These are information attractions in which the context for a purchase is a critical element. For example, many suppliers, especially those of complex products, tend to use an administrative approach in setting their price to help ensure sale price is maintained marginally above cost.

In an advanced technology market, new technologies will need greater thermodynamic depth to achieve market disruption and domination. The thermodynamic depth challenge is an explanation for Bloom et al.'s, recent findings that research productivity is falling in advanced economies (Bloom et al., 2020). An economic (production) system's behaviour follows that of biological systems in production as both are driven by the same physical system behaviour in resource acquisition and production.

5.2. Analogues of Biosphere Ecological Risks in an Economy

The market as a physical resource ecology is a zero-sum physical bounded system which can be viewed as consisting of different trophic production levels (see **Figure 11** below). **Figure 11** applies ecological hierarchy to an economic market

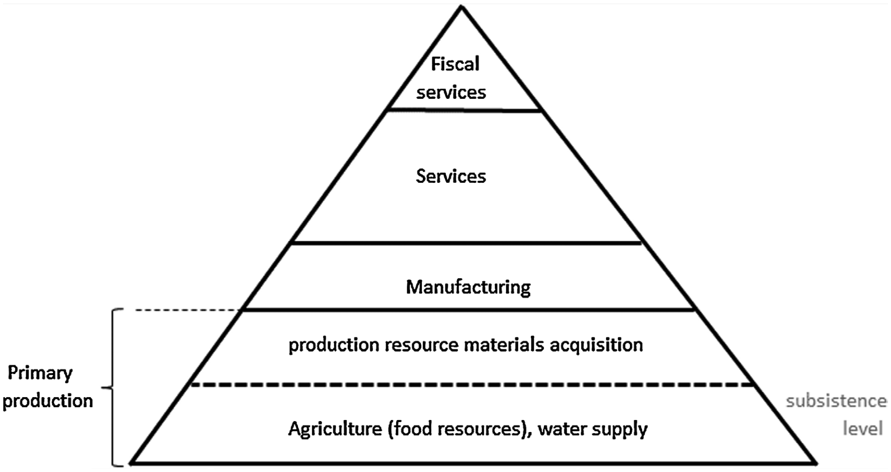


Figure 11. Emergence of production diversity in an economy from the physical characteristics of production. As in biological systems, primary production (production or acquisition of resources essential for human survival) provides the physical resource platform for primary resource surplus production which in turn provides surplus value that is transferred by some form of value-exchange system (e.g. money) into new products and services. An Eltonian pyramid has been used here to describe the exergy redistribution throughout a human economy across five very coarsely defined areas of activity.

as the environment. This structure arises in the same way ecological niches are filled in biology. Feedback on resource use and information utilization (knowledge use and technology development) generates market diversity in the economy once surplus production can be maintained above subsistence level. The primary production level of the economy at subsistence represents pre-Neolithic limitations on value creation. The emergence of the neolithic 'package' of increased social hierarchy able centralize resource returns and redistribute surplus of the common wealth through a value exchange system diversified human economic activity.

This physical bottleneck (subsistence without reproducible surplus production) on the evolution of diversity and complexity in economic activity for the human resource economy has a direct analogue in the evolution of Earths biosphere. Life on Earth remained at the level of prokaryotes for approximately half the current life of the biosphere restricted from evolving more complex life forms by the physical limitations on energy production within prokaryotic cells. Then one social (symbiotic) evolutionary development (the mitochondrion) led to the emergence of eukaryote forms from which complex multicellular life could evolve (Lane, 2015).

To date there have been two human productivity de-bottlenecking evolutionary breakthroughs in the evolution of the human resource economy. The first was the emergence of the neolithic 'package' integrating surplus production with a value exchange system and a centralized authority directing diversification of economic activity. There was a second much more recent bottleneck in per capita GDP productivity in the economy that was overcome by an increase in objective (scientific) knowledge supporting mechanization which led to exponential growth in human productivity. That same utilization of information created an objective knowledge platform that supported exponential human population growth (as described previously for the UK in **Figure 8**).

Analysing a market as a physical resource ecosystem identifies that is fundamentally fueled by its primary productivity and will have a maximum bearing capacity for predatory and parasitic functions within the ecology. There is evidence for that principle applying to a market and its bearing capacity for financial functions which parasitize primary production or predate it (Hudson, 2015; Cecchiti & Kharroubi, 2015; Tori & Onaran, 2017).

The most successful approach to modeling complex behaviour such as that which occurs in an economy can be provided by systems analysis of the critical parameters and their feedback into the system such as the recent work of Farmer (Farmer, 2024). We know this approach is successful at long term prediction of simple critical physical parameters on a global basis because this physical system modelling approach was first attempted over 50 years ago and we have been able to compare the model scenarios to 50 years of global economic history. Physical systems modelling of global resources and entropic effects (e.g. pollution) was first developed in 1972 and the results published in "Limits to Growth" (Meadows et al., 1972; Meadows & Tapley, 2004). The Club of Rome "World" 3 model that generated the 1972 report (Meadows et al., 1972) was composed of five physical variables (population, food (per capita), non-renewable resources, Industrial production per capita and pollution) which were subject to 4 growth scenarios for the global economy, as follows:

- Business as Usual (BAU = current non-renewable resource consumption).
- Business as Usual 2 (double the non-renewable resource consumption of BAU).
- CT (Comprehensive Technology—new technologies boosting growth above 1972 levels).
- SW (Stabilized World—regulation of population and economic growth).

The outcomes for the scenarios were:

- collapse from natural resource depletion in BAU
- collapse from pollution in BAU2
- rising costs from technology investment in CT but no collapse
- stabilisation of population and human welfare in SW

Over thirty years later the World 3 model was reviewed against current global data and found to still be accurate (Turner, 2008). Over a decade after that review the World 3 model scenarios were again reviewed independently (Branderhorst, 2020; Herrington, 2021) and the BAU2 scenario was found by both researchers to still accurately match current global status. No other economic model to date has demonstrated the predictive accuracy provided by this system -based physical model (Bardi & Pereira, 2022).

The analyses undertaken in this paper explain why World 3 has provided such accuracy and longevity: the global economy production relies on physical resources and is affected by the entropy (energy and material dispersion) it creates. The current high level of labour productivity in the global economy is provided by mechanized production which is critically dependent on energy and the complex products needed in mechanized production. Even information utilization for information products is physical and demands resources and information utilization creates diminishing returns on resource use in products of increased complexity. Furthermore, thermodynamic principles are part of economic growth (Ayres, 1998; Ayres & Warr, 2010; Ayres, 2014; King, 2016; Palmer & Alford, 2018; Sverdrup et al., 2018; King, 2021; Ayres et al., 2022; Ayres, 2023; Santos et al., 2021) and production in biological systems in general.

Another example of an ecological behaviour shared by an economy and biological systems, is how intense competition in the environment (market) for space and resources suppresses species (product)diversity. The physical product development and competition factors discussed in this section imply that a small number of highly successful products for a given market niche, will inevitably come to dominate a market—unless the environment (market) itself is altered.

In market ecology terms (see **Figure 11**) this translates into there being a positive role for regulation to avoid or manage a trend towards monopolization of a given market and retain higher market diversity. In the absence of regulation of any particular market, intense resource and customer competition will create a high level of competitor extinction leading to a market power—law distribution and Pareto outcome (a small number of dominating service providers securing the majority of market share). In complex systems behaviour, high adaptation pressure suppresses diversity.

Within a global market dominated by mechanized production and subject to the complexity challenge for technology development by labour, there are physical drag factors on productivity that now need to be included in economic analysis or we will waste capital and resources on bad investments for growth. The risk profile for the global economy is complicated by our current insufficiency of rate of shift to low economic entropy energy resources because climate change has its own "known unknowns"—there are several tipping factors for climate change which have been identified (Newman & Noy, 2023; Steffen et al., 2018; Wunderling et al., 2021) which could take climate change beyond the effective agency of our interventions if we fail to act on fossil fuel entropy damage quickly enough.

6. Conclusion

Physical systems analysis is already being used in economics. Extending it with the level of thermodynamic analysis described in this paper provides the final element needed achieve physical systems analysis that fills the information gaps in contemporary economic growth modeling so that we can accurately identify and manage the emerging risks to sustaining the global economy.

Resource limitations emerge in materially closed systems such as the Earth well in advance of all resources being exhausted. They emerge as a consequence of exponential growth and exponential economic entropy production well before then, emerging as diminishing returns on investment in growth. We currently observe those effects as secular stagnation from both diminishing returns on information utilization and accumulating erosion of natural capital from the effects of pollution on the physical resource base of the global economy. Failure to incorporate these physical risks in economic modeling will result in failed economic planning.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

Ayres, R. U. (1998). *Turning Point: An End to the Growth Paradigm.* Earthscan.

Ayres, R. U. (2014). *The Bubble Economy.* MIT Press.

Ayres, R. U. (2023). Entropy, Exergy, Information and Complexity. In R. U. Ayres (Ed.), *The History and Future of Economics* (pp. 179-194). Springer International Publishing.

https://doi.org/10.1007/978-3-031-26208-1_13

Ayres, R. U., & Warr, B. (2010). *The Economic Growth Engine: How Energy and Work Drive Material Prosperity.* Edward Elgar Publishing. https://doi.org/10.4337/9781848445956

Ayres, R. U., Savin, I., Bergh, J. V. D., & Hao, L. (2022). Exergy versus Labour in Aggregate Production Functions: Estimates for Ten Large Economies. *International Journal of Exergy, 38,* 320-559. https://doi.org/10.1504/ijex.2022.124175

Bakshi, B. R., Gutowski, T. G., & Sekulic, D. P. (2011). *Thermodynamics and the Destruction of Resources.* Cambridge University Press. https://doi.org/10.1017/CBO9780511976049

Bardi, U., & Pereira, C. A. (Eds.) (2022). *Limits and Beyond: 50 Years on from the Limits to Growth, What Did We Learn and What's Next?* Publ. Exapt Press.

Bar-On, Y. M., Phillips, R., & Milo, R. (2018). The Biomass Distribution on Earth. *Proceedings of the National Academy of Sciences of the United States of America, 115,* 6506-6511. https://doi.org/10.1073/pnas.1711842115

Bernanke, B. S., & Gürkaynak, R. S. (2001). *Is Growth Exogenous? Taking Mankiw, Romer, and Weil Seriously.* MIT Press.

Bloom, N., Jones, C. I., Van Reenen, J., & Webb, M. (2020). Are Ideas Getting Harder to Find? *American Economic Review, 110,* 1104-1144. https://doi.org/10.1257/aer.20180338

Branderhorst, G. (2020). *Updating Limits to Growth: Comparing the World 3 Model with Empirical Data.* Ph.D. Thesis, Harvard University.

Cardillo, M. (2002). The Life-History Basis of Latitudinal Diversity Gradients: How Do Species Traits Vary from the Poles to the Equator? *Journal of Animal Ecology, 71,* 79-87. https://doi.org/10.1046/j.0021-8790.2001.00577.x

Cecchiti, S., & Kharroubi, E. (2015). *Why Does Financial Sector Growth Crowd Out Real Economic Growth?* BIS Working Papers No. 490.

Cullen, J. M., & Cooper, D. R. (2022). Material Flows and Efficiency. *Annual Review of Materials Research, 52,* 525-559. https://doi.org/10.1146/annurev-matsci-070218-125903

Faber, M, Niemes, H., & Stephen, G. (1995). *Entropy, Environment and Resources. An Essay in Physico-Economics* (2nd ed.). Springer-Verlag.

Farmer, J. D. (2024). *Making Sense of Chaos. A Better Economics for a Better World.* Allen Lane.

Flemming, H., & Wuertz, S. (2019). Bacteria and Archaea on Earth and Their Abundance in Biofilms. *Nature Reviews Microbiology, 17,* 247-260. https://doi.org/10.1038/s41579-019-0158-9

Frieden, B. R., & Gatenby, R. A. (2005). Power Laws of Complex Systems from Extreme Physical Information. *Physical Review E, 72,* Article ID: 036101. https://doi.org/10.1103/physreve.72.036101

Gowlett, J. A. J. (2016). The Discovery of Fire by Humans: A Long and Convoluted Process. *Philosophical Transactions of the Royal Society B: Biological Sciences, 371,* Article ID: 20150164. https://doi.org/10.1098/rstb.2015.0164

Grove, M. (2009). Hunter–gatherer Movement Patterns: Causes and Constraints. *Journal of Anthropological Archaeology, 28,* 222-233. https://doi.org/10.1016/j.jaa.2009.01.003

Henckens, M. L. C. M., van Ierland, E. C., Driessen, P. P. J., & Worrell, E. (2016). Mineral Resources: Geological Scarcity, Market Price Trends, and Future Generations. *Resources*

Policy, 49, 102-111. https://doi.org/10.1016/j.resourpol.2016.04.012

Herrington, G. (2021). Update to Limits to Growth: Comparing the World3 Model with Empirical Data. *Journal of Industrial Ecology, 25,* 614-626. https://doi.org/10.1111/jiec.13084

Hoek, T. A., Axelrod, K., Biancalani, T., Yurtsev, E. A., Liu, J., & Gore, J. (2016). Resource Availability Modulates the Cooperative and Competitive Nature of a Microbial Cross-Feeding Mutualism. *PLOS Biology, 14,* e1002540. https://doi.org/10.1371/journal.pbio.1002540

Holland, J. H. (1996). *Hidden Order: How Adaptation Builds Complexity.* Basic books/Perseus Books Group.

Holland, J. H. (1998). *Emergence: From Chaos to Order.* Oxford University Press.

Hudson, M. (2015). *Killing the Host. How Financial Parasites and Debt Destroy the Global Economy.* ISLET-Verlag.

Jacques, P., Delannoy, L., Andrieu, B., Yilmaz, D., Jeanmart, H., & Godin, A. (2023). Assessing the Economic Consequences of an Energy Transition through a Biophysical Stock-Flow Consistent Model. *Ecological Economics, 209,* Article ID: 107832. https://doi.org/10.1016/j.ecolecon.2023.107832

Kahneman, D. (2011). *Thinking Fast and Slow.* Random House.

Kahneman, D., & Tversky, A. (1979). Prospect Theory: An Analysis of Decision under Risk. *Econometrica, 47,* 263-292. https://doi.org/10.2307/1914185

Kelley, K., Cartolano, M., & Ferrara, S. (2024). Seals and Signs: Tracing the Origins of Writing in Ancient South-West Asia. *Antiquity, 99,* 64-82. https://doi.org/10.15184/aqy.2024.165

King, C. W. (2016). Information Theory to Assess Relations between Energy and Structure of the U.S. Economy over Time. *BioPhysical Economics and Resource Quality, 1,* Article No. 10. https://doi.org/10.1007/s41247-016-0011-y

King, C. W. (2021). *The Economic Superorganism: Beyond The Competing Narratives on Energy, Growth and Policy.* Springer.

Komlos, J. (2022). *A Probabilistic Theory of Supply and Demand.* https://www.paecon.net/PAEReview/issue102/Komlos102.pdf

Lane, N. (2015). *The Vital Question: Why Is Life the Way It Is?* Profile Books Ltd.

Lloyd, S., & Pagels, H. (1988). Complexity as Thermodynamic Depth. *Annals of Physics, 188,* 186-213. https://doi.org/10.1016/0003-4916(88)90094-2

Marquet, P. A., Quiñones, R. A., Abades, S., Labra, F., Tognelli, M., Arim, M. et al. (2005). Scaling and Power-Laws in Ecological Systems. *Journal of Experimental Biology, 208,* 1749-1769. https://doi.org/10.1242/jeb.01588

Meadows, D., & Tapley, E. (2004). *Limits to Growth: The Thirty Year Update.* Chelsea Green.

Meadows, D., Donella Meadows, D., Randers, J., & Behrens, W. (1972). *The Limits to Growth.* Universe Books.

Nagy, B., Farmer, J. D., Bui, Q. M., & Trancik, J. E. (2013). Statistical Basis for Predicting Technological Progress. *PLOS ONE, 8,* e52669. https://doi.org/10.1371/journal.pone.0052669

Newman, M. (2005). Power Laws, Pareto Distributions and Zipf's Law. *Contemporary Physics, 46,* 323-351. https://doi.org/10.1080/00107510500052444

Newman, R., & Noy, I. (2023). The Global Costs of Extreme Weather That Are Attributable to Climate Change. *Nature Communications, 14,* Article No. 6103.

https://doi.org/10.1038/s41467-023-41888-1

Noe, R., & Hammerstein, P. (1994). Biological Markets: Supply and Demand Determine the Effect of Partner Choice in Cooperation, Mutualism and Mating. *Behavioral Ecology and Sociobiology, 35,* 1-11. https://doi.org/10.1007/bf00167053

Nordhaus, W. D. (2017). Revisiting the Social Cost of Carbon. *Proceedings of the National Academy of Sciences of the United States of America, 114,* 1518-1523. https://doi.org/10.1073/pnas.1609244114

Olson, J. M. (2006). Photosynthesis in the Archean Era. *Photosynthesis Research, 88,* 109-117. https://doi.org/10.1007/s11120-006-9040-5

Palmer, S. J. (2018). The Thermodynamic Forces Driving Natural Selection and Their Evolutionary Consequences. *Journal of Biological Physics and Chemistry, 18,* 5-20. https://doi.org/10.4024/04pa18a.jbpc.18.01

Palmer, S. J. (2019). A Review of the Physical Roles of Information in Nature. *Journal of Biological Physics and Chemistry, 19,* 22-40. https://doi.org/10.4024/3pa19r.jbpc.19.01

Palmer, S. J. (2023a). A Review of Recent Trends in Quantum Thermodynamics and a System's Behavioural Analysis of the Universe Originating as a Quantum Energy System. *Journal of Modern Physics, 14,* 60-71. https://doi.org/10.4236/jmp.2023.141004

Palmer, S. J. (2023b). Physically Defining Life: A Thermodynamic Systems Analysis of Biology. *London Journal of Research in Science, 23,* 41-60.

Palmer, S. J., & Alford, H. (2018). A Thermodynamic Model for the Global Economy and Its Implications for Macroeconomic Theory and Policy Formulation. *Theoretical Economics Letters, 8,* 2741-2771. https://doi.org/10.4236/tel.2018.812173

Palmer, S., Noone, G., & Hoyland, G. (2020). A Review of Physical Relationships between Form and Function in Wastewater Biotreatment and a New Theory Relating Activated Sludge and Biofilm Systems Behaviour. *Water and Environment Journal, 35,* 148-157. https://doi.org/10.1111/wej.12614

Paniccià, R., Piacentini, P., & Prezioso, S. (2013). Total Factor Productivity or Technical Progress Function? Post-Keynesian Insights for the Empirical Analysis of Productivity Differentials in Mature Economies. *Review of Political Economy, 25,* 476-495. https://doi.org/10.1080/09538259.2013.807673

Prigogine, I., Nicolis, G., & Babloyantz, A. (1972). Thermodynamics of Evolution. *Physics Today, 25,* 23-28. https://doi.org/10.1063/1.3071090

Sahal, D. (1979). A Theory of Progress Functions. *A I I E Transactions, 11,* 23-29. https://doi.org/10.1080/05695557908974396

Santos, J., Borges, A. S., & Domingos, T. (2021). Exploring the Links between Total Factor Productivity and Energy Efficiency: Portugal, 1960-2014. *Energy Economics, 101,* Article ID: 105407. https://doi.org/10.1016/j.eneco.2021.105407

Sauvet, G. (2019). The Lifeworld of Hunter-Gatherers and the Concepts of Territory. *Quaternary International, 503,* 191-199. https://doi.org/10.1016/j.quaint.2017.01.040

Smith, A. (1776). *The Wealth of Nation.* Penguin Classics.

Smith, A. (1790). *The Theory of Moral Sentiments* (6th ed). Penguin Classics.

Smith, E. A., & Codding, B. F. (2021). Ecological Variation and Institutionalized Inequality in Hunter-Gatherer Societies. *Proceedings of the National Academy of Sciences of the United States of America, 118,* e2016134118. https://doi.org/10.1073/pnas.2016134118

Solow, R. M. (1956). A Contribution to the Theory of Economic Growth. *The Quarterly Journal of Economics, 70,* 65-94. https://doi.org/10.2307/1884513

Solow, R. M. (1957). Technical Change and the Aggregate Production Function. *The Re-*

view of Economics and Statistics, 39, 312-320. https://doi.org/10.2307/1926047

Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D. et al. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences of the United States of America, 115,* 8252-8259. https://doi.org/10.1073/pnas.1810141115

Sverdrup, H., Olafsdottir, A. H., Ragnarsdottir, K. V., Koca, D., & Lorenz, U. (2018). The WORLD7 Integrated System Dynamics Model: Examples of Results from Simulations. In *Progress towards the Resource Revolution* (pp. 67-76). World Resources Forum.

Tori, D., & Onaran, O. (2017). The Effects of Financialisation and Financial Development on Investment: Evidence from Firm-Level Data in Europe. *SSRN Electronic Journal.* https://doi.org/10.2139/ssrn.3064062

Turner, G. (2008). A Comparison of the Limits to Growth with 30 Years of Reality. *Global Environmental Change, 18,* 397-411. https://doi.org/10.1016/j.gloenvcha.2008.05.001

von Stockar, U. (2013). Live Cells as Open Non-Equilibrium Systems. In U. von Stockar (Ed.), *Biothermodynamics: The Role of Thermodynamics in Biochemical Engineering* (pp. 399-421). EPFL Press

Warr, B., Ayres, R., Eisenmenger, N., Krausmann, F., & Schandl, H. (2010). Energy Use and Economic Development: A Comparative Analysis of Useful Work Supply in Austria, Japan, the United Kingdom and the US during 100years of Economic Growth. *Ecological Economics, 69,* 1904-1917. https://doi.org/10.1016/j.ecolecon.2010.03.021

Wells, J. C. K., & Stock, J. T. (2020). Life History Transitions at the Origins of Agriculture: A Model for Understanding How Niche Construction Impacts Human Growth, Demography and Health. *Frontiers in Endocrinology, 11,* Article 325. https://doi.org/10.3389/fendo.2020.00325

Woodburn, J. (1982). Egalitarian Societies. *Man, 17,* 431-451. https://doi.org/10.2307/2801707

Wunderling, N., Donges, J. F., Kurths, J., & Winkelmann, R. (2021). Interacting Tipping Elements Increase Risk of Climate Domino Effects under Global Warming. *Earth System Dynamics, 12,* 601-619. https://doi.org/10.5194/esd-12-601-2021

Appendix: Supporting Information for Section 3.2—The Physical Basis of Production in Biological Systems

The simplest independent forms of life to emerge on Earth are the prokaryotes (comprising the Eubacteria and Archaea), which are both descended from a Last Universal Common Ancestor (LUCA) (Lane, 2015; Palmer, 2018; Palmer, 2019; Palmer, 2023b). The prokaryotes are the life-forms from which all other life on Earth has evolved.

To maintain the cell and reproduce, prokaryotic cell systems acquire energy and material resources from their environment, in competition with other prokaryote species when they utilise the same resources. To produce and maintain the complex structure of the cell and its inheritable chemical memory (genes) requires physical work (Prigogine et al., 1972; von Stockar, 2013; Lane, 2015; Palmer, 2018; Palmer, 2019; Palmer, 2023b).

This creates a high demand for energy resources (von Stockar, 2013; Lane, 2015; Palmer, 2023b). To produce cells, biological systems also require material resources for cell structures which are built by anabolic processes (von Stockar, 2013; Lane, 2015; Palmer, 2023b). The high energy demand of cell (re)production is met by coupling catabolic energy release to anabolic processes via an electron transport chain. The absolute dependence of living systems on energy for reproduction is reflected in an aspect of human economic behaviour being present and hardwired into the earliest forms of life: an energy currency, a form of value exchange for energy emerging in the form of ATP/ADP (von Stockar, 2013; Lane, 2015).

Life emerged on Earth in a cellular form similar to prokaryotes between 3.4 to 4.3 billion years ago (3.4 to 4.3 Ga) (von Stockar, 2013; Palmer, 2018). These prokaryotic cells have a cell wall that allows them to maintain an internal environment through regulation of their physiology. The ability to grow and reproduce is critically dependent on energy resources (von Stockar, 2013), in the form of catabolic substrates which are catabolised to release the free energy needed to build and maintain the prokaryotic cell and reproduce it in the earliest forms of life. Later, by 3.0 GA, evolution of sulphur based photosynthetic energy capture in prokaryotes (Olson, 2006) introduced utilization of solar energy as an energy source for cell growth starting the line of evolution that shifted the Earth to an oxidising atmosphere through oxygenic photosynthesis and led to the emergence of plants (Olson, 2006; Lane, 2015).

For the earlier heterotrophic and chemically autotrophic prokaryotes, the free energy obtained from catabolic chemical reactions is coupled to anabolic processes that build and maintain the cell to a genetic code blueprint provided by that species' genome (Lane, 2015; Palmer, 2018; Palmer, 2023b). Prigogine (Prigogine et al., 1972) demonstrated how open physical systems, including chemical and biological systems, are able to form low entropy structures (complex structures) at the temperatures that support life. **Figure A1** and **Figure A2** below illustrate how the intensity of energy resource and material resource acquisition required for reproduction results in living systems maintaining themselves a significant distance from thermodynamic equilibrium.

In the process of cellular (re)production anabolic activity within the cell produces a complex structure with significant thermodynamic depth (high information content which equates to low entropy) (Palmer, 2019).

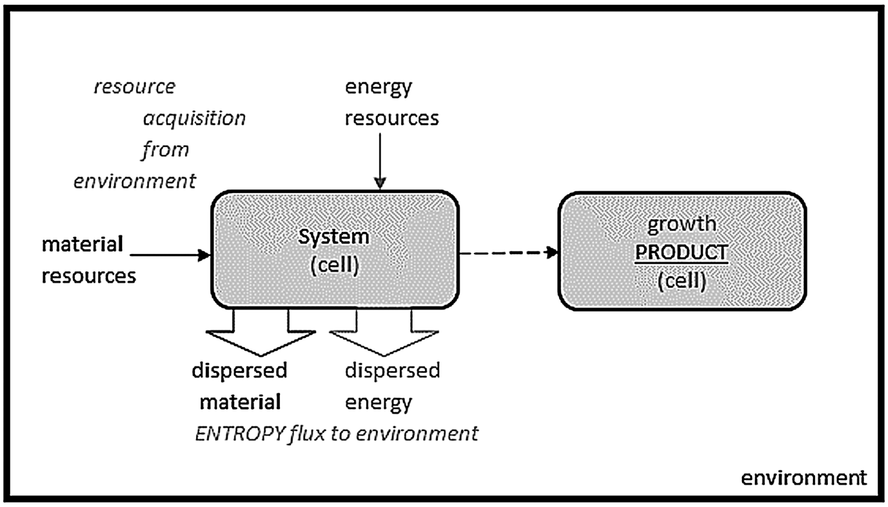

Figure A1. Biological production. Production requires physical work to be done which consumes free energy (exergy) and material resources and inevitably, due to the 2nd Law of thermodynamics, dissipates energy and waste materials into the environment (von Stockar, 2013; Lane, 2015; Palmer, 2018; Palmer, 2019; Palmer, 2023b). The level of resource consumption depends on the thermodynamic depth (physical information complexity) of the product. The greater the thermodynamic depth of the product (Lloyd & Pagels, 1988), the more extensive and deeper the information demands or production are. In the human economy, energy is also a critical resource for growth (Ayres & Warr, 2010; Warr et al., 2010; King, 2016; Palmer & Alford, 2018; King, 2021), fulfilling the same role in enabling production work that it does in biological growth. In order to create a low entropy structure, the productive unit, the cell, exports entropy to its environment (see **Figure 2** and **Figure 3** in the main text and **Figure A1** above), in this case in the form of simple catabolites (such as the carbon dioxide of **Figure A2** below) and metabolites. The entropy balance for cells reacting chemicals *j* at constant temperature and pressure is:

$$S_{\mathrm{prod}} = \Sigma \mathrm{j} - \Delta \mathrm{rjG/T}\ \xi j + \mathrm{W/T} + \Sigma \mathrm{j}\ \mu_i\ \dot{\imath}\mathrm{n/T} - i\ \mu_{\mathrm{i}}\mathrm{out/T)}\ n_{j,\mathrm{in}} \qquad \text{(A1)}$$

where S_{prod} is the entropy produced from the Gibbs reaction energy −ΔrjG, W work done, ‘T’ is temperature, μ_i the chemical potential of the ‘i’th component, ξj = rate of the *j*th chemical reaction and $n_{j,in}$ is the influx flow) (von Stockar, 2013).

For information to have utility to a system it needs to have a register—a form of memory. This is in fact the creates the defining difference between biological systems and physical/chemical systems to give a universal definition of life:

A biological system is a self-reproducing chemical system with a chemical memory configured by evolution in reference to its environment, which affords the system the ability to adapt to its environment (Palmer, 2023b).

All biological systems are learning systems (Palmer, 2018; Palmer, 2023b). Competition for space is between species is driven by use of information to better adapt to the environment than other competing species, from generation to generation by gene mutation but information is also used within the life cycle of prokaryotic cells through cell regulation and chemical sensing—quorum sensing. Proteomic and genetic studies over the last three decades have a developed a deeper understanding of the sophistication of information in the environment including identifying the role that sensing plays, via quorum sensing, in how prokaryote cells adapt to their environment within their own life cycle (Palmer, 2023a). Sensing provides information on the status of the environment within the life cycle of an organism, allowing it to continuously adapt its behaviour to environmental risks. Quorum sensing in prokaryotes has evolved to allow them to adapt to two basic resource challenges in their environment: unlimited resources or limited resources (Palmer, 2023b).

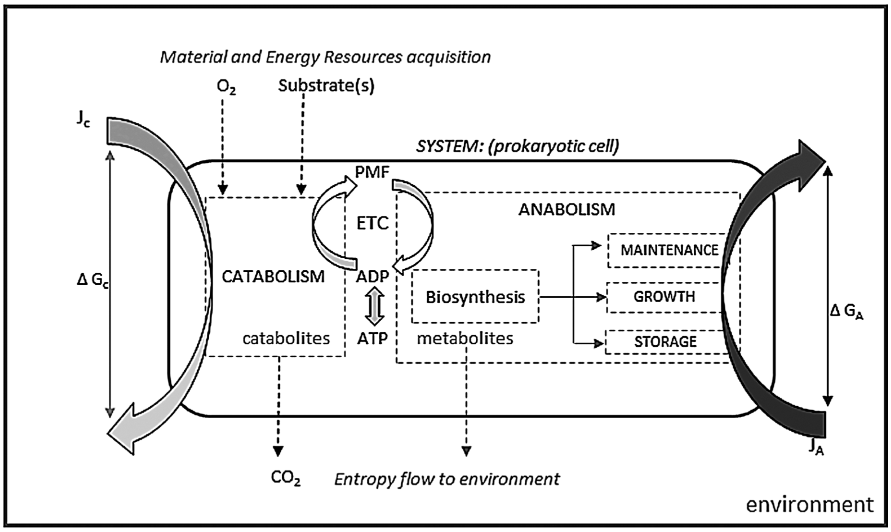

Figure A2. Systems diagram for energy and materials balance for prokaryotic cells. This coupling sustains a driving force J_A for anabolic activity from the energy sink of force J_c. Force J_c is maintained by the exergy provided by Gibbs energy released by catabolism (ΔG_c) which in turn creates a driving force J_A for cell reproduction (growth). The origin of force J_c counterbalancing force J_A is the system entropy balance and the system attempting to return to equilibrium with its environment (von Stockar, 2013; Palmer, 2023b).

Quorum sensing allows prokaryotes to shift cell regulation between two fundamental strategies for growth based on resource availability in the environment, known in ecology as "r" and "K" strategies. When resources are unlimited, there is a competitive advantage in rapid growth at a maximum rate (r-strategy), which translates into maximum rate of resource consumption and entropy discharge to the environment. Quorum sensing allows a shift to a more resource efficient and resilient cell regulation represented by "K" growth strategy. When resources are limited quorum sensing in prokaryotes also shifts the mode of growth to social and commensal growth in biofilms to optimize overall muti-species return on resources (Palmer, 2023b).

Prokaryotes, representing the most basic form of independent life formed the basis of primary production in Earth's biosphere until photosynthesis evolved within prokaryotes. Prokaryotes dominated the biosphere until a cell form with greater energy capacity (emergence of eukaryotic cells (Lane, 2015) which in turn allowed the emergence of a diversity of even more complex multicellular organisms. Even today prokaryotes constitute 6% of the biomass in Earths biosphere and the majority of that is thought to be present as social (cooperating) prokaryote structures (biofilms) (Flemming & Wuertz, 2019; Bar-On et al., 2018; Palmer, Noone, & Hoyland, 2020), see **Figure A3** below.

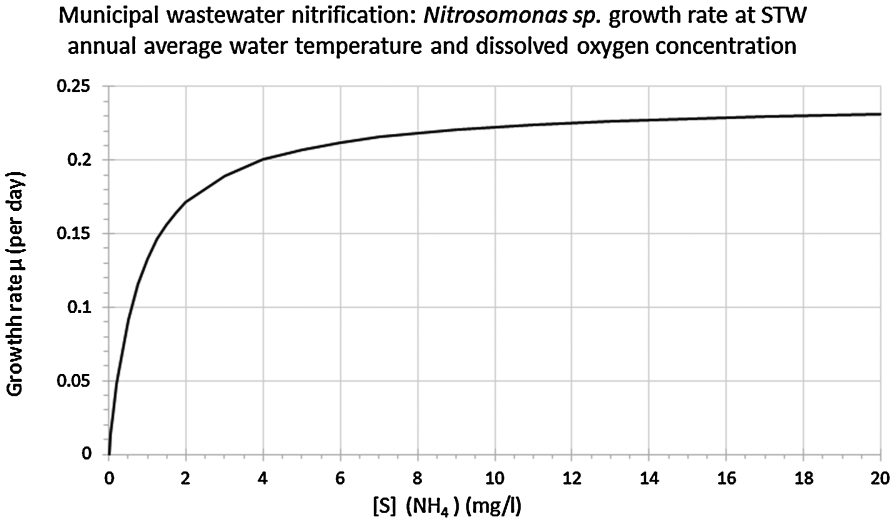

Figure A3. Single prokaryote species growth on a single substrate and production system productivity limits. A critical resource-utilization saturation relationship. The growth rate follows a diminishing return in terms of on resource availability in a system as the physical (bioenergetic) limits on cell size limit the catabolic enzyme production capacity, Hence reaction rate (catabolic substrate removal rate) diminishes with increasing catabolic enzyme capacity (processing capacity) eventually becoming saturated. For this particular aerobic autotrophic bacterial genus (Nitrosomonas sp.), the genome size that its niche energy resource (ammonia) supports limits its bioenergetic returns which in turn limits how large a genome it can develop. In contrast, heterotrophic aerobic bacteria best adapted to wastewater are able to generate more energy per mass of catabolic resource oxidized to a degree that allows them reproduce faster—but they have also evolved a genome specifying catabolic enzymes for a small range of oxidizable soluble carbon molecules. These bacterial species practice resource substitution—they can substitute one growth limiting resource for another. Resource efficiency and parsimony enforces an evolved sequential use and substitution of production limiting catabolic resources, based on the highest net energy return being specified as the first for use by the gnome when it is present in the environment. Even when critical resource substitution can be deployed, growth by prokaryote species can lead to resource depletion in their environment (see **Figure A5** further below for impact on growth/production growth trajectory) and a need to adapt to resource limitation to maximize species survival (increase species persistence in the environment).

The universal systems behaviour of biological systems, described above at the level of the simplest independent organisms (prokaryotes), can be summarized in systems behaviour terms as one of utilization of environmental information to adapt reproduction to environmental conditions. The thermodynamics of the coupling of catabolism, providing the energy for growth processes, to anabolic processes providing growth follows the Monod relationship:

$$\mu = \mu_{max}\left[S\right]/kS+\left[S\right] \tag{A2}$$

where μ is growth rate, μ is maximum possible growth rate for that species on catabolic substrate [S], [S] is the limiting substrate concentration and kS is the rate of catabolic (limiting) substrate uptake by the species) (Palmer, 2023b).

Critically, in terms of information about production, the rules established for biomass production in prokaryotes acknowledge the effect of entropy on production and organism longevity as cell regulation as described above allows for resources to be attributed to cell maintenance in order to extend the productive period for the production system. The cell-biomass yield Y_{DX} from anabolism coupled to catabolism is a function of the distribution of energy (resources) that cell regulation sets between reproduction (growth) and cell maintenance (von Stockar, 2013), see **Figure A4** below.

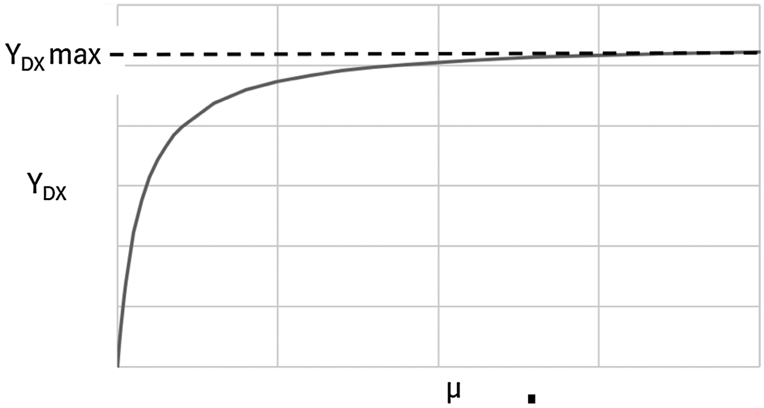

Figure A4. The effect of critical resource (catabolic energy) distribution between prokaryote cell growth and maintenance growth. Limits to production come from critical (i.e. rate-limiting) resources, not the whole resource profile.

$$Y_{DX} = Y_{DX\,max}\Big/\left(1+mD\cdot Y_{DX\,max}/\mu\right) \tag{A3}$$

where μ is growth (production) rate, $Y_{DX\,max}$ is maximum cell yield Y_{DX} (productivity) for that species on its catabolic substrate, subject to critical resource (the catabolic energy produced, being distributed between cell maintenance mD and growth by cell regulation (von Stockar, 2013).

Which results from the entropy of cell production in terms of a decay coefficient existing for the production system (cell) which creates a need for a balancing investment in production to maintain the same level of production;

$$k_d = mD\cdot Y_{DX\,max} \tag{A4}$$

These are the production relationships and their resource demands for all prokaryotes on Earth, organisms which provide a large part of Earth's primary production.

The actual growth rate observed is hence a function of information utilization by a prokaryote species in terms of the organism sensing which catabolic substrate is present of those it can catabolize, initiating enzyme production for that resource and also regulating which growth strategy the species follows in that environment based on the ratio of food to cell numbers in quorum sensing.

- When resources are limiting, cell physiology shifts towards increased cell persistence (more resources to cell maintenance and resource storage (termed 'K' strategy for growth in ecology).
- When resources are unlimited, growth at maximum rate is possible and all resources are directed to cell reproduction (termed "r" strategy for growth in ecology) (Palmer, 2023b).

The productivity of information utilizing systems (e.g. all biological systems) in their environment reflects the information available in their genome and the sensing that the genome confers as this represents information use within the life cycle. That sensing is directed at establishing the relationship between environment and organism and individual success but the intergenerational feedback into the genome comes from reproductive success and total population numbers. Prokaryote (re)production follows characteristic population trends when single species are grown on one substrate in a materially closed system, as shown in **Figure A5** below.

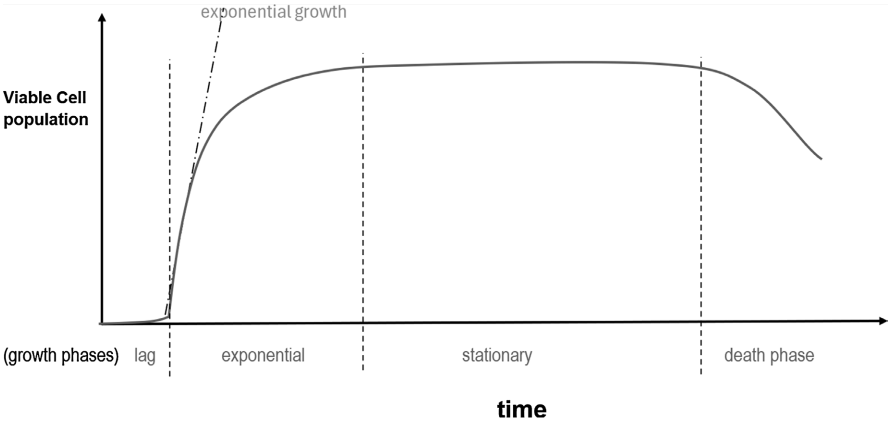

Figure A5. Single prokaryote species growth on a single substrate in a materially closed system. In the lag phase, the organism is adjusting to its environment via (quorum) sensing, using the information in its genome to set the cell for optimum reproduction in that environment, then followed a maximum (exponential) production phase (growth rate) which that environment supports until resources become depleted (in the stationary phase). Ultimately the viable cell count drops as viable cells begin to die off under starvation.

The behaviour of biological populations in their environment and how they compete for space and resources is reflected in their ecology. Resource utilization for production (growth) often follows a power-law distribution in biology and ecology because utilization of information to adapt to the environment is common throughout biology within life an organism's life cycle as well as its adaptation to environment between generations via mutations in DNA. The system complexity associated with biological productivity arises from the system behaviour being complex (see **Figure A6** below).

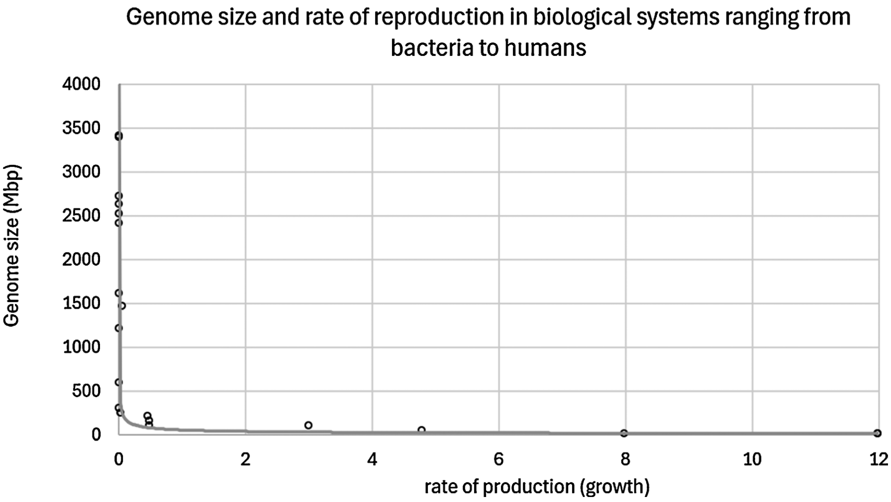

Figure A6. Organism doubling time as a function of species genome size. Genome size for a sample of 20 species ranging from prokaryotes to *Homo sapiens* shows how a species rate of production varies with average rate of reproduction—following a power-law relationship (with a log-log linear regression of 0.82 for this sample set). Biomass production rate as doubling time in prokaryotes decreases with increased genome size (Palmer, Noone, & Hoyland, 2020) and the same general trend appears to apply across a wider range of species. Complex adaptive systems (such as biological systems) often show long -tailed power law distributions of system behavior (Holland, 1996; Holland, 1998; Friedan & Gatenby, 2005; Marquet et al., 2005; Newman, 2005).

Biological species are populations of organisms and those organisms are structurally and mechanically complex and increasingly so in multicellular organisms. Consequently, in terms of thermodynamic information, as organism complexity increases thermodynamic depth (Lloyd & Pagels, 1988) increases.

The resource distribution strategy that has emerged from evolution in biological systems demonstrates a genome-embedded trend in resource utilization that is most obvious in prokaryotes because of their relative simplicity. In the lag phase prokaryotes with quorum sensing use quorum sensing to assess the resource level in its environment reactive to the population and then invest resources into growth at a maximum possible rate of cell reproduction when critical resources are unlimited (“r” growth strategy). If a quorum sensing prokaryote species determines critical resources are limited and sensed as being so in the lag phase, cell regulation shifts to maximize individual cell resilience by increasing energy and resource flow into cell maintenance and storage (von Stockar, 2013).

As evolution fills ecological niches in an environment, increased diversity of complexity under natural selection is needed to create new resource opportunities and niches. The information provision in biology for adaptation resides in a species genome. The genome can therefore be analysed as an indicator of thermodynamic depth. **Figure A6** examines this relationship. **Figure A6** shows that as species genome size and thermodynamic depth increases, it takes longer to reach reproductive age and reproduce. This is thermodynamically equivalent to the rate of production decreasing as the product becomes more complex, which has profound implications for information use in economic production.

At the simplest level in biological systems (prokaryotes), species survival and resilience is relatively easy to discern as a function of a genome encoding a growth strategy for resource limited conditions (forms of ecological "K" strategy) or for unlimited resource conditions (forms of ecological "r" strategy) (Palmer, Noone, & Hoyland, 2020; Palmer, 2023b). This capability is encoded at the start of independent life in prokaryotes (see comparative growth rate and persistence in the environment under r and K strategies in **Figure A7** below).

This evolved strategy for resource selection arises from the probability of a species success and survival in the environment. In an environment with unlimited critical resources, competition for space and domination of that environment is more probable for the fastest reproducing species. In contrast, systems using information (biological systems) from sensing in an environment with limited critical resources, are able to us genome encoded survival traits to maximize population longevity and persistence, as that will maximize species survive until new resources enter the environment or until the species moves to another environment. Survival and longevity of the species tends to favour cooperative and social resource acquisition once resources become limiting.

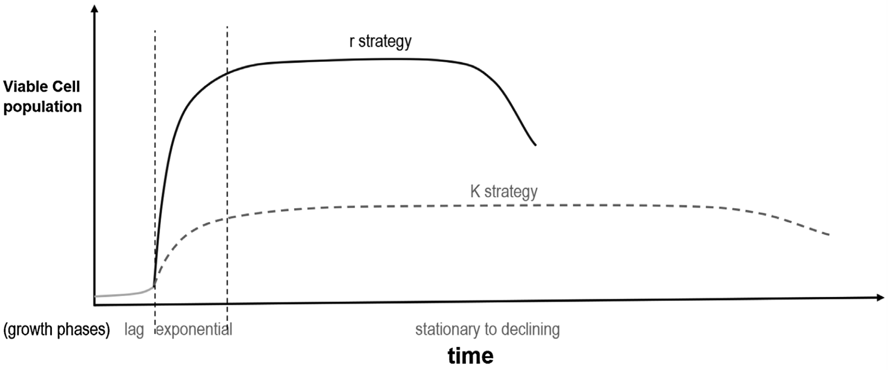

Figure A7. Single prokaryote species single substrate growth in a materially closed system with different initial catabolic substrate concentrations. In the lag phase, the organism is adjusting to its environment via (quorum) sensing and one of two growth strategies ("r" strategy or "K" strategy) is then pursued based on the ratio of its population to available critical resources based on whether critical resources are unlimited or limited (Palmer, Noone, & Hoyland, 2020; Palmer, 2023b). Whichever growth strategy is pursued, production of cells increases the entropy of the materially closed system which accumulates as production continues. In any closed system production completely collapses due to entropy accumulation unless new resources are secured or energy can enter the system to support the recycling of resources within the system. Utilization of information by biological systems on Earth has supported evolution that has developed photosynthesis which has allowed recycling of resources on Earth, using energy from outside Earth (solar energy).

For large animal ecology, there are known cases where the same general "r" and "K" strategy trend appears to apply in relation to overall resource availability in the environment, although it can be harder to identify with more complex organisms. Entropy creates the pyramid structure for energy transfer into living systems on Earth because typically only 10% of the energy going into new biomass formation transfers up into the next trophic level with the rest dissipating into the environment (as in **Figure A8**).

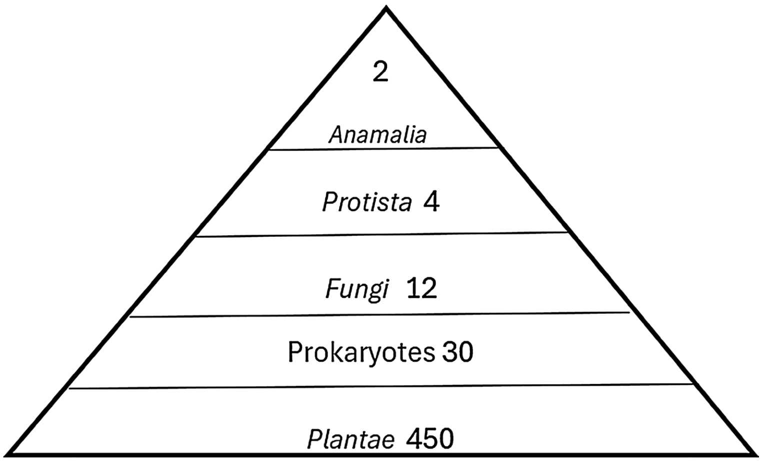

Figure A8. Current Earth Biomass Trophic Pyramid showing biomass trophic levels in terms of their carbon mass (in billion tonnes Carbon). The biosphere currently sequesters 500 Billion tonnes of Carbon. Primary production in the Earth-system has been dominated by photosynthesizing organisms (Plantae and photosynthesizing prokaryotes, since the evolution of photosynthesis in photosynthesizing prokaryotes (Lane, 2015; Olson, 2006; Cardillo, 2002; Bar-On et al., 2018). However, currently primary production is provided by plants (Plantae) and prokaryotes (Eubacteria and Archaea) with primary consumption of plants by animals and fungi and primary consumption of prokaryotes mainly by protists. Animals only provide 0.4% of the global biomass of which 20% are terrestrial animals and 9% are mammals. Humans and their domesticated animals completely dominate the land mammal biomass forming 98% of it. Only 2% of remaining land mammals are wild (Cardillo, 2002; Bar-On et al., 2018).

These trophic resource factors have global outcomes. At the equator, where primary production and resources are richer, the higher resource bearing capacity for multiple competing species allows more competition, whereas in climate zones further from the equator where resources are more limited, "K" reproductive strategy based on fewer more resilient offspring is more prevalent (Palmer, Noone, & Hoyland, 2020). For ecologies that include predators or parasites, there is a maximum bearing capacity of that environment for the predatory load and parasitic load on the system.

- **Environmental system limits configure biological system behaviour.**

Biological systems are complex and so ecology is complex. The reason why biological system behaviour is complex arises from what defines biology: a biological system is a self-reproducing chemical system with a chemical memory configured by evolution in reference to its environment, which affords the system the ability to adapt to its environment. The process of a species maintaining fitness to persist in its environment is one of it using information about the environment to configure itself to the environment—a continuous feedback that creates complexity in behaviour.

That complexity makes it difficult to identify generic ecological strategies that emerge in biology for resource acquisition for reproduction unless that analysis is focused on the least complex biological systems—such as prokaryotes. Over 2 billion years of evolution and adaptation in prokaryotes has deeply conserved two fundamental strategies for resource acquisition: individual-focused reproduction at maximum rate tends to dominate in resource-rich environments but species-survival based reproduction at slower rates of reproduction maximizes fitness for species persistence in resource limited environments.

Fitness in resource limited environments is increased through maximising population persistence which in turn is optimized by maximizing efficiency of resource use which itself is optimized by social behaviour (Palmer, 2023b; Flemming & Wuertz, 2019; Noe & Hammerstein, 1994; Hoek et al., 2016). In prokaryotes two forms of multicellular growth emerged in resource limited environments: formation of forms of biofilm or filamentous growth (Palmer, Noone, & Hoyland, 2020).

Both are based on species survival being driven at the population level in resource limited environments and of the two, biofilm formation is the most ubiquitous because it confers a further advantage of supporting multispecies cooperative growth. The ability for form a biofilm, is an obvious extended phenotype—it configures the local environment around the species initiating the biofilm such that such that other prokaryote species can grow in association with that forming a biofilm (Palmer, Noone, & Hoyland, 2020).