# The Economics of EcoSocieties

# Chapter 1:  Introductory Concepts

I remember as a small boy once having a very good idea: collect all the electricity coming from the dynamo on my bicycle and feed it into a motor to drive the bicycle. Bingo, a perpetual motion machine. OK, I was young and naive. But whatever your level of science, most people would feel uneasy at the notion of limitless energy. 'You don't get something for nothing'. 'No such a thing as a free lunch'.

The real tragedy today, however, is that much of modern politics and economics is devoted to encouraging us to believe 'you do get something for nothing, if you're smart enough.' There is a growing dislocation between the emotionally driven world of politics, economics, media, and advertising on the one hand, and the science, technology, and laws of nature on the other. It's almost like they speak entirely different languages, or worse still, one language with two distinct dictionaries. To such an extent that a large fraction of our GNP is effectively now spent on schemes that defy the laws of nature.

The most frequently mocked law of nature in this regard is the scientifically revered *conservation of energy*. The conservation of energy has been tested to phenomenal accuracy and found to hold in every case studied. Starlight from the edge of the observable universe shows exactly the same energy levels as from a burning candle here on earth. Unknown particles of physics had to be postulated – and subsequently discovered decades – where tiny anomalies of energy appeared in a deeply probing experiments of high energy physics.

The conservation of energy is like the last bastion of physics; it is the last product of the rational mind when all else seems to fail. If energy goes missing somewhere – if more energy goes in than comes out – then something is wrong with the measurements, a tiny mistake in the energy accounting. The 'before' and 'after' amounts must tally, as in a perfect double-entry bookkeeping system. There is no energy 'spillage' in nature. The flux of energy through an ecosystem, is the one firm rock from which to observe and measure the ebbs and flows of a myriad of energy transformations and exchanges through a complex and evolving ecosystem (or ecosociety).

The flux of energy through an ecosystem on this planet, starts with incident sunlight across the planet. High energy photons power the process of photosynthesis in a plant cell, transforming the photon energy into energy-rich molecules of biochemistry. Energy-rich molecules then diffuse throughout the plant cell, driving further molecular reactions powering cell repair, cell growth and cell division.

Science would say the photon energy has been fixed by the plant cell into usable energy (glucose) and non-usable energy (heat waste). The start and finish energy totals must be identical, under conservation of energy. The trick that living cells perfected over 3 billion years of genetic variation and selection, is to design and build (by degrees) a chemical power house that extracts as much useful energy as possible from the environment, while minimizing the amount of wasted energy (molecular vibrations, rotations, infrared radiation, etc).

Then, after 3 billion years, comes along a new type of life, an animal cell which consumes plant cells, sequestering the energy rich molecules for its own purposes, driving its own cell repair, cell growth and cell division. At all points and at all times energy must be conserved: tot up the various energies distributed around the system, tot up all the waste energy, and you get precisely what goes in as photon energy.

The energy subtotals around the system, distributed in its various forms and within the various species gives you (in energy terms) the spectrum of biomass across the ecosystem. Conservation of energy allows you to quantitatively track in detail the energy flux through the entire system and its subsystems, starting from the total photon energy input at one end, to the total infrared energy output at the other (see diagram).

# Chapter 2: Unicellular growth

Some 3.7 billion years ago, a species of bacteria, very much like the modern day cyanobacter, were already flourishing in shallow seas and lakes across the entire planet. With a chemical processing complexity vastly exceeding that of a modern petrochemical refinery, featuring intricate feedback control systems to speed up or slow down each or all the individual metabolic pathways of more than 40,000 distinct processes and intermediate metabolites, the humble bacterium today, is a marvel of ancient biochemical engineering, virtually unchanged in functionality or efficiency over the last 3.7 billion years. The DNA specification of the metabolic pathways component is 99.9% identical across all species of lifeforms thriving on the planet today, for the simple reason that all present day cells incorporate 'copyright' versions of those ancient bacteria, as part of their cellular makeup.

Amid all the myriad of side reactions and catalytic processes that go into controlling, directing and optimizing the metabolic pathways of life, the fundamental chemical outcome consolidates down to one simple chemical reaction, the 'life equation' reaction :

$$CO_2 + H_2O + \text{photon energy} \rightarrow CH_2O + O_2$$

$CO_2$ and $H_2O$ diffuses into the cell, the (toxic) byproduct $O_2$ diffuses out of the cell, while the energy rich $CH_2O$ molecule is carefully spirited away from the reaction site for the purposes of cell growth and maintenance.

Not only is energy conserved in this equation, so is mass. Specifically, one Carbon, three Oxygen, two Hydrogen atoms go into this reaction and one Carbon, three Oxygen, two Hydrogen atoms come out of this reaction, albeit rearranged into different molecular forms.

Bacteria being small (approx $10^{-6}$ m), molecular diffusion is sufficient for this process to proceed at a rapid pace, rapid enough that under optimal growth conditions, some bacteria can double their mass (and numbers) within 20 minutes.

So phenomenal is this rate of growth that, were it to continue for just 48 hours, one bacterium will grow into a colony of some $10^{33}$ Kg in mass, a biomass far exceeding the mass of the Earth (see appendix). Clearly, unlimited growth is never possible in nature, optimal growth conditions never last for very long. Sooner, rather than later, one of more of the four molecular reactants in the life equation become rate-limiting.

The five reactants (if you include photon energy) are always rate-limiting in the natural world. In fact the life equation is perfectly reversible:

plants →

$$CO_2 + H_2O + \text{photon energy} \leftrightarrow CH_2O + O_2$$

← animals

Animal cells use the reverse reaction to power their growth, as do plant cells during the night or winter months. Plants drive the reaction from left to right. Animals drive the reaction from right to left. Plants consume $CO_2$ and evolve $O_2$. Animals consume $O_2$ and evolve $CO_2$. Both in strict numerical coupled proportions to each other.

A steady balance of $O_2$ and $CO_2$ is therefore sustainable given a constant input flux of high energy photons from sunlight. Currently on Earth, atmospheric $O_2$ and $CO_2$ are approximately 20% and 0.04%, though these figures have varied substantially throughout geological ages, reflecting (among other things) the shifting dominance of plant and animal growth on the planet.

Simple calculations show that at the current levels of plant growth on this planet, atmospheric $CO_2$ would deplete in four months, were it not replenished by animal growth. In other words, the turnover of atmospheric $CO_2$ takes only four months. Furthermore, atmospheric $CO_2$ represents only 2% of the total carbon currently fixed as plant-animal biomass. The planet's ecosystem is running at full capacity, and is rate-limited by the atmospheric $CO_2$ concentration.

Such simple considerations demonstrate that the animal-plant ecosystem on earth already persists under tight equilibrium, with only relative changes in species proportions within each kingdom being possible. A microbiologist would say, the struggle for survival on this planet has gone from batch culture with exponential growth, to a continuous steady state culture, all growth now being rate-limited by the photon flux across the planet.

Any further net growth in total plant-animal biomass can arise only from the release of subterranean reserves of $CO_2$ via volcanoes, melting tundra, limestone uplift. Far from fretting about current levels of atmospheric $CO_2$, humans should be wondering what happens when this non-atmospheric carbon supply extinguishes (as it has already, on Mars).

However, this book is more concerned with quantifying the energy flux through the various physical and chemical forms in an ecosystem or eco-subsystem, where a eco-subsystem may range from a single plant or animal cell, to a single multicellular organism (plant or animal), to an entire community of plants and animals, such as the present day ecosystem on Earth (before humans – but see chapter 5).

We are able to do this solely because, subsisting beneath the myriad of physical, chemical and biological interactions, lies one all-encompassing absolute truth of nature: the conservation of energy. At no time within any (closed) system can energy be created or destroyed.

As a consequence, our entire ecosystem must subsist solely on the sun's steady flux of high energy photons from sunlight – approximately 1000 Watts per square meter of the planet. The scramble for chemical energy, the struggle to survive, across the entire planet has become a zero sum game: your energy loss is my energy gain. It's a sobering thought that the entire planet's ecosystem subsists on an energy diet of just 1000 $W/m^2$, roughly the heat output of a kettle (per square meter).

# Chapter 3:  Multicellular Growth

While plant and animals cells appeared relatively soon after the planet cooled sufficiently to permit running water, it took nature a full 3 billion years to perfect it's next major innovative lifeform: multi-cellular organisms.

In this chapter we consider a multicellular organism as an ecosystem of individual cells, a coordinated colony of (genetically) identical cells (typically numbering $10^{13}$ or more), all cooperating to extract usable energy from its environment at the maximum rate. The degree of efficiency achieved by any one individual organism being ruthlessly and systematically culled by natural selection: individuals who can extract usable energy more efficiently have the greater chance of passing on their genes (and efficiency) to their next generation.

We see from the life equation, the rate of energy extraction by a cell is quantitatively determined by the concentrations of all five reactants in its immediate environment, typically a sphere of water $10^{-6}$ m in size. At such small distances, molecular diffusion through water is more than adequate to transport substrates and products in and out of the cell interior. We also saw that the transport in both directions is  equally important (quantitatively coupled, in fact). Any one of the four concentrations can at any time become rate-limiting to the rate of energy extraction, and hence to the rate of cell growth. Diffusion problems provide the overriding limit to cell size: cells much bigger than $10^{-6}$ m suffer disadvantageously from slower rates of molecular diffusion.

A major evolutionary leap occurred with the arrival of multicellular organisms on Earth. Huge colonies of (genetically) identical cells could now form a very tightly coupled community of cells, all striving in unison to be the organism with the most optimized energy extraction system, the one able to out-compete all other multicellular and unicellular organisms within their habitat.

Having commandeered lock stock and barrel an entire factory of metabolic pathways, laboriously perfected over billions of years by the unicellular kingdom, multicellular organisms now concentrated on perfecting the next level in organizational structure and logistic control required for the efficient energy extraction. The energy extraction by an entire colony of some $10^{13}$ individual cells, acting in unison for a common good, the common good now being the survival and prosperity of the organism as a whole.

It is clear from the sheer numbers involved (over $10^{13}$ cells in the human body) that this would always involve a major organizational undertaking. The fact that, through the 'trial and error' of natural selection, the same solution to the same organization problem has been discovered and rediscovered many times over by nature, through countless trials, throughout countless different environments and extremes, proves how stable and robust the multicellular solution has become to life on Earth. The former once dominant unicellular forms, are now mainly confined to the roles of scavenging around and parisitizing within multicellular lifeforms on the planet.

So how does nature solve this enormous problem of running at full capacity a huge society of $10^{13}$ individual cells? The answer is staggeringly simple. It is also starkly sombre. It (nature) dictatorially assigns – via the genetic blueprint of an organism's physiological structure – the precise quantitative specifications and functional capacity for each component and subcomponent of the organism's physiological structure.

If the overall blueprint leads to a multicellular organism better adapted in some way to survive the struggle for existence, then its genes will propagate advantageously at the expense of all others, and so lead on to another round of improvement and selection. It is clear that such a ruthless process is unlikely to brook such energy wasting concepts as competition, greed, self-interest and autocracy at the individual cell level.

Effectively, every cell in the organism is required to sign a 'social contract': supply the organism with your (specialty) energy rich goods/services (via the circulatory system) at the prescribed rate, and the organism will supply you (via the circulatory system), and in strict quantitative proportion to your output, all your input requirements to perform at that rate. In brief, total and absolute cooperation: the energy flux being equal and binding. It is the circulatory system that delivers and enforces the cooperative efforts of $10^{13}$ cells in a multicellular organism: it is the circulatory system that is the logistics of energy flux throughout the organism.

And in return for a stable, predictable and constant supply of goods and services, every cell throughout the organism is required to surrender its ultimate destiny – the ability to reproduce – effectively guaranteeing its early demise. There are no known exceptions in nature to this organizational law on multicellular organisms; those that do seem to arise on occasion, rapidly prove to be uncompetitive and lethal to the organism (such as cancer). Intriguingly, when it comes to full-on competition or full-on cooperation in its ecosystems, nature shows little enthusiasm for any half way house solutions.

In multicellular organisms we also see another of nature's innovative steps, which is only of limited utility in unicellular lifeforms: the mass hording or storage of long-term, high-energy storage molecules within special 'energy dumps' (such as specialized fat depositing cells in mammals).

Energy storage comes with its own advantages and disadvantages. Energetically it is costly: both the storage and subsequent recovery of useful energy is itself energetically costly. High levels of fat storage cause further energy losses: the need to carry around large unproductive extra mass, causes diminished speed speed and agility, a heavy burden in the animal kingdom. The balance between improved survival and diminished agility is an equation each organism must solve in each environment; typically energy storage mechanisms are advantageous in habitats suffering large environmental fluctuations and disadvantageous in less fluctuating environments. In this sense, energy storage mechanisms act as an internal buffer to environmental fluctuations.