Sustainable systems as organisms?

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Abstract

Schrödinger [Schrödinger, E., 1944. What is Life? Cambridge University Press, Cambridge] marvelled at how the organism is able to use metabolic energy to maintain and even increase its organisation, which could not be understood in terms of classical statistical thermodynamics. Ho [Ho, M.W., 1993. The Rainbow and the Worm, The Physics of Organisms, World Scientific, Singapore; Ho, M.W., 1998a. The Rainbow and the Worm, The Physics of Organisms, 2nd (enlarged) ed., reprinted 1999, 2001, 2003 (available online from ISIS website www.i- sis.org.uk)] outlined a novel "thermodynamics of organised complexity" based on a nested dynamical structure that enables the organism to maintain its organisation and simultaneously achieve non-equilibrium and equilibrium energy transfer at maximum efficiency. This thermodynamic model of the organism is reminiscent of the dynamical structure of steady state ecosystems identified by Ulanowicz [Ulanowicz, R.E., 1983. Identifying the structure of cycling in ecosystems. Math. Biosci. 65, 210–237; Ulanowicz, R.E., 2003. Some steps towards a central theory of ecosystem dynamics. Comput. Biol. Chem. 27, 523–530].

The healthy organism excels in maintaining its organisation and keeping away from thermodynamic equilibrium – death by another name – and in reproducing and providing for future generations. In those respects, it is the ideal sustainable system. We propose therefore to explore the common features between organisms and ecosystems, to see how far we can analyse sustainable systems in agriculture, ecology and economics as organisms, and to extract indicators of the system's health or sustainability.

We find that looking at sustainable systems as organisms provides fresh insights on sustainability, and offers diagnostic criteria for sustainability that reflect the system's health.

In the case of ecosystems, those diagnostic criteria of health translate into properties such as biodiversity and productivity, the richness of cycles, the efficiency of energy use and minimum dissipation. In the case of economic systems, they translate into space-time differentiation or organised heterogeneity, local autonomy and sufficiency at appropriate levels, reciprocity and equality of exchange, and most of all, balancing the exploitation of natural resources – real input into the system – against the ability of the ecosystem to regenerate itself.

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1. What is life?

Schrödinger (1944) wrote: "It is by avoiding the rapid decay into the inert state of 'equilibrium' that an organism appears so enigmatic... What an organism feeds upon is negative entropy. Or, to put it less paradoxically, the essential thing in metabolism is that the organism succeeds in freeing itself from all the entropy it cannot help producing while alive."

In a footnote, Schrödinger admitted that by "negative entropy", he perhaps should have said free energy; but the latter did not really have the right connotation. What he wished to capture was the ability of the organism, not only to avoid the effects of entropy production – as dictated by the second law of thermodynamics – but to do just the opposite, to increase in organisation, which intuitively, seems like the converse of entropy.

Schrödinger was struggling to make explicit the intimate relationship between energy and organisation. To make progress, we need to see life with fresh eyes.

By half accident, one of us discovered that all living organisms look like a dynamic liquid crystal display when viewed under the polarising light microscope that geologists use to look at rock crystals and other birefringent materials (Ho and Lawrence, 1993; Ho et al., 1996; Ross et al., 1997). The fact that living moving organisms, with all their molecules churning around transforming energy could appear like a dynamic liquid crystal display is evidence that living organisms are coherent (organised) to a high degree, right down to the alignment and motions of the protein molecules in their tissues and cells (Ho, 1993, 1998a).

There is obviously something very special about the way the organism uses energy that harks back to Schrödinger's "negative entropy", which will be made more explicit in a reformulation of thermodynamics (presented in detail elsewhere (Ho, 1998a)). This turns out to have features in common with the dynamical structure of ecosystems that Ulanowicz (1983, 2003) has identified previously. We shall explore the similarities between sustainable ecosystems and economic systems on the one hand and the ideal organism on the other, with a view to extracting diagnostic signs of health or sustainability for the system concerned. Preliminary versions of these ideas were presented earlier (Ho, 1997, 1998b).

2. Sustainable systems as organisms?

Looking at sustainable systems as organisms is not such an outrageously novel or outlandish idea. The idea of 'ecosystem as organism' is hardly foreign to ecology; Clements (1916) was an ardent champion early last century, although ecologists in general had roundly rejected it after the mid 1950s.

Here, we use the term 'organism' without invoking consciousness or will, or that it need follow a rigid programme of development. As Ulanowicz (2001) pointed out, subtracting those still leaves one with a significant residuum of organic-like behaviour, such as homeostasis, and dynamic wholeness or coherence that is the hallmark of an organism.

At a Royal Society conference, Abrupt Climate Change (2003), many speakers drew attention to records from the ice and deep-sea cores, which showed detailed globally correlated changes in temperature and carbon dioxide concentrations on our planet, going back at least 800,000 years. These do give the impression that the earth has been behaving from moment to moment as one coherent whole, rather like a 'superorganism' – called Gaia by Jim Lovelock – that has sustained life for billions of years (Bunyard et al., 2003).

But the organism can be sick, as the earth's ecosystem has been sickened by the excessive and wasteful uses of fossil fuel since industrialization, and abrupt climate change is happening, according to the gathering of experts. That is presumably why we are increasingly suffering extremes of climate, heat waves, floods, droughts, hurricanes, accelerated melting of the polar ice caps and the sea levels rising.

One of the most important questions raised by climate change is whether we can still grow enough food to feed ourselves.

Lester Brown (2003) of the Earth Policy Institute writes of the dire state of our planet, and rightly blames the economy: "We have built an environmental bubble economy, one where economic output is artificially inflated by overconsumption of the earth's natural assets. The challenge today is to deflate the bubble before it bursts." Furthermore, he thinks that the most vulnerable economic sector may be food.

The United Nations Food and Agricultural Organisation (FAO) defines food security as follows: "When all people, at all times, have physical and economic

access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy live."

For that to be satisfied under climate change, we need sustainable agriculture as well as a sustainable economy.

For one thing, conventional industrial agriculture is heavily dependent on oil and water (Odum, 1971), both fast diminishing; conventional industrial agriculture is very energy intensive, and becoming increasingly unproductive as temperature soars during the growing season and the soil is eroded and depleted (Brown, 2003). Climate change will force us to adopt sustainable, low input agriculture to genuinely feed the world, and to ameliorate its worst consequences (Goldsmith, 2004).

Thus, it is important to discover what makes a system sustainable, as Eugene Odum (1969) has long championed, both in agriculture and in economics, and how we may restore a system to health.

3. How organisms make a living

Sustainability has become a buzzword, co-opted by many when they mean the opposite. So rather than defining it, we shall try to show that there is a lot we can learn about sustainability by studying how organisms sustain themselves, i.e., keep alive and well.

The pre-requisite for keeping away from thermodynamic equilibrium – death by another name – is to be able to capture energy and material from the environment to develop, grow and recreate oneself from moment to moment during one's life time. The organism not only sustains itself dynamically, it also reproduces future generations, which is part and parcel of sustainability.

An organism has physical barriers that separate inside from the outside, but never completely. It can be questioned whether such physical closure is necessary. More important than physical closure is dynamic closure, that enables the organism to store as much energy and material as possible (a tendency called "centripetality" by Ulanowicz, 1997), and to use the energy and material most efficiently, i.e., with the least amount of waste and dissipation (see later).

The organism has solved its problems of sustainability over billions of years of evolution. It has

an obviously nested physical structure. Our body is enclosed and protected by a rather tough skin, but we can exchange energy and material with the outside, as we need to, we eat, breathe and excrete. Within the body, there are organs, tissues and cells, each with a certain degree of autonomy and closure. Within the cells there are numerous intracellular compartments that operate more or less autonomously from the rest of the cell. And within each compartment, there are molecular complexes doing different things, such as transcribing genes, making proteins and extracting energy from our food. More importantly, the activities in all those compartments, from the microscopic to the macroscopic are perfectly orchestrated, which is why the organism looks like a dynamic liquid crystalline display, as explained earlier.

The key to understanding the thermodynamics of the living system may not be energy flow, as suggested previously (Prigogine, 1967; Morowitz, 1968; Ulanowicz, 1983), as much as energy capture and storage under energy flow (Fig. 1). Energy flow is of no consequence unless the energy can be trapped and stored within the system, where it is mobilised to give a self-maintaining, self-reproducing life cycle coupled to the energy flow. (By energy, we include material flow, which enables the energy to be stored and mobilised.)

The approach taken here appears, at first glance, to diverge significantly from the framework established by earlier applications of thermodynamics to ecology. The importance of energy capture and storage – rather than energy flow – may be appreciated by comparing earth, a planet filled with life and maintained far away from thermodynamic equilibrium as a whole, with our
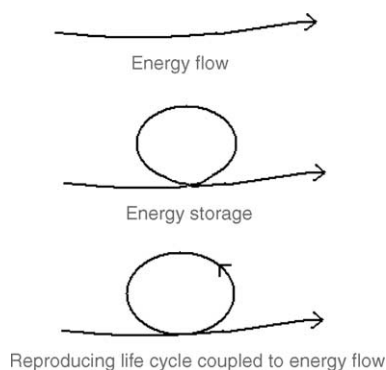

Fig. 1. Energy flow, energy storage and the reproducing life cycle.

neighbouring planet mars, which is at thermodynamic equilibrium and in all probability, lifeless. Earth has succeeded in capturing and storing the energy from the sun through inventing chlorophyll some 3.5 billion years ago, in the first cyanobacteria.

However, Hannon and Ulanowicz (1987) pointed out that if one were to look at the entropy balance as calculated from incident and efferent spectra, earth would stand out as more dissipative than the other planets, or in other words, it has 'degraded' the incoming energy much more completely. And this would appear contradictory to the claim made earlier that organisms should use energy with the minimum of dissipation.

But if more of the incoming energy is captured and stored within the earth ecosystem, as is claimed here, then it is entirely consistent with efferent spectra being much more diminished than if the sun's radiant energy is simply reflected back: a perfect reflecting mirror would be the 'least dissipative'. There are obviously deeper conceptual problems that need to be addressed.

4. Stored energy, exergy and free energy

Fraser and Kay (2002) distinguished between two ways to represent thermodynamic efficiency from the perspective of engineering. The most common is the "first law" sense in terms of the least amount of waste or dissipation, which appears superficially to be what we are suggesting above. Instead, efficiency in the "second law" sense is where one regards the amount and quality of the incoming energy. A system is most efficient when it extracts as much useful work from that energy before releasing it back to the universe; i.e., it releases energy in a more degraded (higher entropy) form. To do this the system usually has to be more dissipative. Hence, systems that are efficient in the second law sense of the word would tend to be more dissipative (Hannon and Ulanowicz, 1987).

Fraser and Kay (2002) defined "exergy" as a "pseudo-property of maximum useful to-the-dead-state work". It is considered a "pseudo-property" because the maximum useful work is a function of the environment, so its magnitude depends on the given environment. Exergy, originally defined by Kestin (1968) is the preferred term used in ecology, and to great effect (e.g., Schneider and Kay, 1994).

In order to avoid confusion, we should state right away that stored energy – to be more explicitly defined later – though related to exergy is distinct from it. Stored energy is perhaps closest to Jørgensen (1992) use of the term exergy, in particular, his idea that ecosystems develop so as to maximise their storage of exergy.

In general, stored energy is more related to the free energy defined by chemists and physicists, especially in the form of Gibbs free energy, $G = U + PV - TS$, where U is the internal energy, P, V, T and S are pressure, volume, temperature and entropy, respectively. In that respect, the distinction between first and second law definition of efficiency, of primary importance for engineers, is not relevant to our use here, as the second law is always subsumed, and assumed to be true; efficiency can never exceed 100%.

There is another respect in which stored energy is distinct from exergy. Exergy is relevant to the workings of heat engines and heat transfer. The organism does not work by heat transfer. To all intent and purposes, it is an isothermal machine (c.f. Morowitz, 1968) dependent on the direct transfer of molecular energy, on proteins and macromolecules acting as "molecular energy machines" (see later). For isothermal processes, the change in Gibbs free energy is:

$$\Delta G = \Delta H - T\Delta S$$

Efficiency as presently defined, requires either that ΔS approaches 0 (least dissipation), or ΔG approaches 0 (free energy conservation, entropy–enthalpy compensation, near equilibrium processes, or far from equilibrium processes, as will be explained later) (see Ho, 1995 for further details).

It is of interest to examine Matsuno and Swenson (1999) "consumer-dominated thermodynamics", which too, predicts the most dissipation. The heat sink – the consumer – most active and effective in extracting heat energy from the incoming source will result in the fastest or greatest temperature drop.

Consumer-dominated thermodynamics was applied to the idea that life on earth may have originated in submarine hydrothermal vents starting from chemical synthesis of complex biological molecules in the hot vents (Corliss et al., 1979). The hot jet from the hydrothermal vents comes quickly into contact with cold seawater, which serves as the heat sink. Chemical products synthesized in the hot vents undergo abrupt

cooling once ejected into the cold environment. According to Matsuno and Swenson (1999), the surrounding heat sink makes consumer-dominating thermodynamics operative: "Only the products exhibiting the fastest temperature drop could survive there." That statement is ambiguous in view of the argument following on: which is that those molecules that survive the sudden drop in temperature best will come to dominate the mixture. In that case, a more appropriate statement would have been: "Only the products best at exploiting the abrupt temperature drop could survive there." Such molecules could well be the ones that have the highest heat capacity, i.e., able to store the highest amount of energy in the ambient temperature imposed.

It is indeed energy storage and mobilisation at a nonclassical steady state that characterise the sustainable living system, as will be made clearer below. We are looking at the energy "consumer" system from within, to discover how it can lead to the fastest temperature drop, or appear to "degrade the thermodynamic gradient" most effectively (Schneider and Kay, 1994).

5. Cycles make sense

The perfect coordination (organisation) of the organism depends on how the captured energy is mobilised within the organism. It turns out that energy is mobilised in cycles, or more precisely, quasi-limit cycles, which can be thought of as dynamic boxes; and they come in all sizes, from the very fast to the very slow, from the global to the most local. Cycles provide the dynamic closure that is absolutely necessary for life, perhaps much more so than physical closure.

Biologists have long puzzled over why biological activities are predominantly rhythmic or cyclic, and much effort has gone into identifying the centre of control, and more recently to identifying master genes that control biological rhythms, to no avail.

The organism is full of cycles, possibly because cycles make thermodynamic sense. Cycles mean returning again and again to the same states; and no entropy is generated in a perfect cycle; in other words, the system as a whole remains organised. Cycles give dynamic stability as well as autonomy to the organism; and this is apparently also the case in ecosystems (Ulanowicz, 1983). Moreover, cycles enable the activities to be coupled, or linked together, so that those
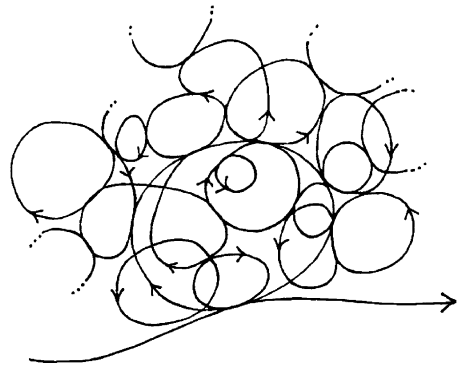

Fig. 2. The life cycle of the organism consists of a self-similar fractal structure of cycles turning within cycles.

yielding energy can transfer the energy directly to those requiring energy, and the direction can be reversed when the need arises. These symmetrical, reciprocal relationships are most important for sustaining the system; and our metabolism is actually organised in that way: closing cycles and linking up.

Fig. 2 is a diagram representing the nested cycles that span all space-time scales, the totality of which make up the life cycle of the organism. Ho (1998a) proposed that the life cycle has a self-similar fractal structure, so if you magnify each cycle, you will see that it has smaller cycles within, looking much the same as the whole. The reason for this will be explained later.

The system effectively stores and mobilises energy over all space-times that are coupled together. Thus, energy can get from any space-time compartment to every other, from the local to the global and vice versa.

This complex nested dynamical space-time structure of the organism is the secret of its sustainability. As will be explained below, it maximises the efficiency and rapidity of energy mobilisation. The degree of space-time differentiation is directly correlated with the amount of energy stored. Both these features are incorporated in the organism's metabolic network ascendancy as described by Ulanowicz (2003) for ecosystems.

6. Redefining the second law for living systems

Physiologist Colin McClare (1971) made an important contribution towards reformulating thermodynamics so that it can apply to living systems. He proposed
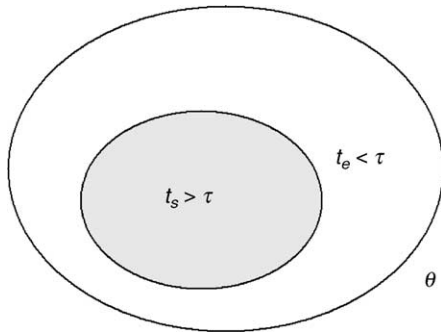
Fig. 3. Stored vs. thermal energy.

that in a system defined by some macroscopic parameter, such as temperature, θ, its energies can be separated into two categories: stored (coherent) energies that remain in a non-equilibrium state within a characteristic time, τ, and thermal (random) energies that exchange with each other and reach equilibrium (or equilibrate) in a time less than τ (see Fig. 3).

McClare thereby introduced time structure into systems, with very important consequences. Because there are now two ways to mobilise energy efficiently with entropy change approaching zero: very slowly with respect to τ, so it is reversible at every point; or very rapidly with respect to τ, so that the energy remains stored as it is mobilised.

For a process with characteristic timescale of 10^{-10} s, a millisecond is an eternity, so a 'slow' process need not be very slow at all to be energy efficient. Most enzyme reactions therefore could be occurring at thermodynamic equilibrium. On the other hand, resonant energy transfer is an example of a very fast process occurring in $<10^{-14}$ s, so the energy remains stored as it is transferred. The latter process too, is very important for living systems. Resonance interactions may coordinate reactions in different parts of the cell. Resonating molecules attract one another, and could be involved in the binding of antigen to antibody and enzyme to substrate (reviewed in Ho, 1998a).

Ho (1993, 1995, 1998a) modified and generalised McClare's proposal to a characteristic space-time of energy storage, with some interesting consequences for the living system.

McClare (1971) proposed that, "Useful work is only done by a molecular system when one form of stored energy is converted into another". In other words, ther-

malised energies cannot be used to do work, and thermalised energy cannot be converted into stored energy. That statement was obviously wrong, and McClare received a lot of criticism for it. Thermalised energies from burning petrol or coal can indeed do work, they are routinely used to run generators and automobiles, which is why they are inefficient.

Actually, McClare was not far wrong; his proposal was incomplete. Ho (1993, 1995) completed his proposal as follows: "Useful work is only done by a molecular system when one form of stored energy is converted into another in the same system." (This may be compared with the Rosen (1991) concept of "self-entailment".)

This entails defining a 'system' by the extent to which thermal energies equilibrate within a characteristic space-time.

Thus, in the case of the automobile, the hot gases expand against a constraint, the piston, which, in taking up the thermalized energy, does work against the system external to the combustion chamber.

This definition of a system is most important for the nested space-time structure of the organism, which is in effect partitioned into a hierarchy of systems within systems defined by equilibration space-times. Thus, energies thermalised or equilibrated within a smaller space-time (system) will still be out of equilibrium in the larger system encompassing the first (see Fig. 4). So, even though the organism as a whole is far from thermodynamic equilibrium, its space-time differentiation nevertheless allows for a hierarchy of local near-equilibrium regimes to be maintained within.

Stored energy is thus equivalent to exergy, as both refer to energy that is available for doing useful work. But stored energy is explicitly defined with respect to a
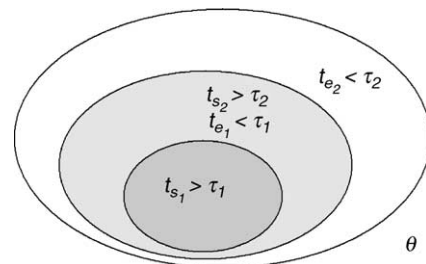

Fig. 4. A nested hierarchy of space-times in which equilibrium and non-equilibrium co-exist.

characteristic space-time, and is hence a real property of systems rather than a pseudo-property as defined for exergy (see earlier).

It is intuitively obvious why the nested space-time differentiation in organisms optimises thermodynamic efficiency: it allows the organism to simultaneously exploit equilibrium and non-equilibrium energy transfers with minimum dissipation. It also optimises the rapidity of energy mobilisation. For example, biochemical reactions depend strictly on local concentrations of reactants, which could be enormously high, depending on their extent of equilibration, which is generally quite restricted. Cell biologists are beginning to take seriously the view that the cell is more like a solid-state, or more accurately, a liquid crystalline mesophase, where nothing is freely diffusible, and even the cell water is organised into polarized multi-layers (reviewed in Ho, 1998a; see also Ling, 2001).

Another point to note is that the more complex the space-time differentiation, the more coherent energy is stored within the system. Because the activities are all coupled together, the energy residence time depends on how many activities there are within the system. In a similar way, the generalised space-time system ascendency would gauge these coherencies (Ulanowicz, 2003; see also Ulanowicz and Ho, 2005).

Finally, and this is crucial, there has to be a structure to the space-time differentiation, so the activities can remain mostly distinct and independent, and yet, are poised to exchange energies with one another. In other words, the energies in different space-time domains need to be separately mobilised; and yet be able to spread from any point to the entire system, and conversely, converge from all over the system to any point. Ho (1998a) surmises that a self-similar fractal organisation provides such a space-time structure, although there is no proof that is the case.

7. Equilibrium and non-equilibrium

The 'thermodynamics of organised complexity' described above is distinct from previous attempts to apply thermodynamics to living systems. It does not say that the living system is to be adequately described by either equilibrium or non-equilibrium thermodynamics. It says that the organism as a whole is far from thermodynamic equilibrium on account

of the enormous amount of stored, coherent energy mobilised within the system, but also that this macroscopically non-equilibrium regime is made up of a nested dynamic structure that allows both equilibrium and non-equilibrium approximations to be simultaneously satisfied at different levels.

In that regard, it differs from Prigogine's (1967) theory of dissipative structures, which argues for representing living systems as regimes far from thermodynamic equilibrium, and Gladyshev (1999) "hierarchic macrothermodynamics" that regards living systems as close to thermodynamic equilibrium. The detailed arguments are presented elsewhere (Ho, 1998a); an abbreviated version is given below.

8. Dynamic balance on the whole

In the ideal – represented by the healthy mature organism as well as the healthy mature ecosystem (Odum, 1969) – the system is always tending towards a dynamic balance or a non-classical steady state (Fig. 5), as will be explained shortly. The simple equation, $\Sigma \Delta S = 0$, inside the cycle, says there is an overall internal conservation of energy and compensation of entropy so that the system organisation is maintained and dissipation minimised (Schrödinger's negentropy); while the necessary dissipation is exported to the outside, $\Sigma \Delta S > 0$.

Internal entropy compensation and energy conservation implies that positive entropy generated somewhere is compensated by negative entropy elsewhere within the organism over a finite time. This is possible only if the internal microscopic detailed balance at every point of classical steady state theory is violated.
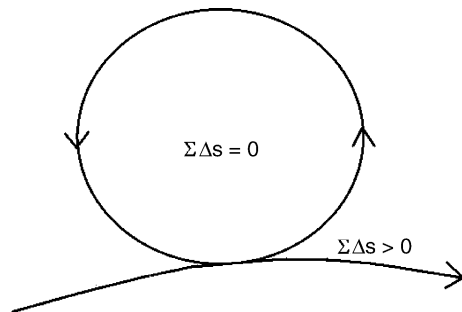

Fig. 5. Dynamic balance of cyclic processes coupled to energy flow.

Denbigh (1951) defined the steady state as one in which "the macroscopic parameters such as temperature, pressure and composition, have time-independent values at every point of the system, despite the occurrence of a dissipative process." That is far too restrictive to apply to the living system. Instead, Ho (1993, 1998a) proposed to define the living system in homeostasis as a "dynamic equilibrium in which the macroscopic parameters, such as temperature, pressure and composition have time-independent values despite the occurrence of dissipative processes." The omission of the phrase "at every point of the system" is significant.

Microscopic homogeneity is not crucial for the formulation of any thermodynamic state, as the thermodynamic parameters are macroscopic entities quite independent of the microscopic interpretations. Like the principle of microscopic reversibility, it is extraneous to the phenomenological laws of thermodynamics, as Denbigh himself had convincingly argued.

It is the organised space-time heterogeneity within the living system that allows for the necessary 'free' variation of the microscopic states within the macroscopic thermodynamic constraints. Thus, stability criteria that apply to the system as a whole need not be satisfied, or stronger yet, cannot be satisfied in every individual space-time element for all times.

There is also minimum entropy production in sustainable systems. The tendency to conserve coherent energy and compensate for entropy production within the system will result in the minimum entropy being exported to the outside. Intuitively, one can see that if the system were maximally efficient, then it would also produce the least dissipation.

From the outside, it would appear that the system is "maximally dissipative" in terms of having "degraded" the energy gradient most effectively. But this ignores the coherent energy stored, not degraded, within the system. One way of estimating stored energy is in terms of standing biomass, which also enters into the measure of system ascendancy (Ulanowicz, 2003).

9. Sustainable systems as organisms and diagnostic signs of sustainability

Ho (1998c) suggested diagnostic criteria of sustainability or health that depend on the tendency of a sustainable system to maximise non-dissipative cyclic flows of energy and minimising dissipative flows.

Ulanowicz (1983) has stressed the importance of cycles in ecosystems, and has developed a way of separating the (conserved) cycled flows from the (dissipative) transit flows. Unlike biochemical cycles in living organisms, however, ecosystem cycles are not immediately reversible: prey-predator relationships are almost always, strictly one-way. Reciprocity is a more general concept than reversibility, and achieves the same result. Thus, the prey can effectively "eat" the predator when the latter dies and decomposes and turns into nutrients for plants that the prey feeds on.

Maximising non-dissipative cyclic flows will increase the following: energy storage capacity, which translates into carrying capacity or biomass; the number of cycles in the system; the efficiency of energy use; space-time differentiation, which translates into biodiversity; balanced flows of resources and energy; reciprocal coupling of processes. The minimisation of dissipation will result in reducing entropy production.

These diagnostic criteria are interlinked, so once one is identified, the others are very likely to follow. Some support for these criteria is that they are similar to those Schneider and Kay (1994) have identified for mature, established ecosystems. They compared the data collected for carbon-energy flows in two aquatic march ecosystems next to a large power-generating facility in the Crystal River in Florida (Homer et al., 1976). One of them, 'stressed', was exposed to hot water coming out of the nuclear power station which increased the temperature by 6 °C, the other 'control', not so exposed, was otherwise similar. They found that the stressed system captured 20% less energy, made 20% less efficient use of the energy captured, had 50% fewer cycles and 34% less biomass than the control.

We shall reanalyse those data in the accompanying note to extract more explicit diagnostic signs of ecosystem health (Ulanowicz and Ho, 2005).

Schneider and Kay (1994) also drew attention to some interesting measurements made by Luvall and Holbo (1991) with a NASA thermal infrared multispectral scanner from the air, which assess energy budgets of terrestrial landscapes. They found that the more developed the ecosystem, the colder its surface temperature. This is consistent with the maximisation of energy storage capacity and the minimisation of dissipation (although their own interpretation is that the

more developed ecosystem is more efficient in degrading the energy gradient (see earlier).

Another indication of the energy efficiency and potential increase in carrying capacity of sustainable systems is provided by a comparison of 25 rice cultivation system, of which eight were pre-industrial in terms of low fossil fuel input (2–4%) and high labour input (35–78%), 10 were semi-industrial with moderate to high fossil fuel input (23–93%) and low to moderate labour input (4–46%) and seven were full industrial with 95% fossil fuel input and extremely low labour input of 0.04–0.2%. The total output per hectare in gigajoule (GJ) in the pre-industrial fell into a low (2.4–9.9) and a high-output (149.3–166.9) subgroup, with the former one-twentieth to one-fifth of the full industrial average. However, the output of the high subgroup was two to three times the full-industrial systems. The yields of semi-industrial systems were more homogeneous, with an average of 51.75 GJ, while the yields of full-industrial systems, even more uniform, averaged 65.66 GJ.

When the ratio of total energetic output to total input was calculated, however, the pre-industrial systems ranged between 6.9 and 11.5, with the figures for the most productive systems as high as 15.3–29.2. Semi-industrial systems gave ratios of 2.1–9.7, whereas the ratios of full-industrial systems were not much better than unity. These figures illustrate the law of diminishing returns quite well: there seems to be a plateau of output per hectare around 70–80 GJ regardless of the total input, which is only exceeded in the three high-yielding pre-industrial systems of Yunnan, China. Intensifying energy input led to a drop in efficiency, particularly sharp as input approaches the output ceiling, which appeared to conform to the notion of a carrying capacity. So how did the Chinese achieve such a high yield, thereby contradicting the notion of a fixed carrying capacity? Could it be due to the use of farmyard and human manure as organic fertilizers that increased soil organic carbon and hence soil fertility?

10. Sustainable economic systems

We can deal with sustainable economic systems by embedding the global economic system in the global ecosystem (Ho, 1998c) (Fig. 6).
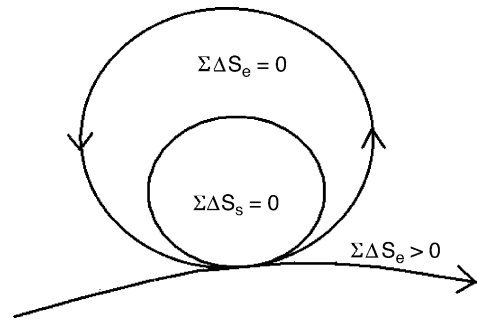

Fig. 6. The coupled flows of the economic and ecological cycles in a sustainable economic system.

The global economic system will have an intricate structure encompassing many national economies. Ideally, the intricate structure of the global economy should look like the many nested subcycles that make up the organism's life cycle (see Fig. 2). And each national economy, in turn, would have its own intricate structure that is self-similar to the global. If the entire global system is to be sustainable, there has to be a proper balance between the local and the global, the same kind of reciprocal, symmetrically coupled relationships that one finds in organisms that results in $\Sigma \Delta S_s = 0$. Furthermore, the global economy is coupled to the global ecosystem, which too, has to have its own balance, represented by $\Sigma \Delta S_e = 0$, so that both can survive.

The economic globalisation promoted by the rich countries in the World Trade Organisation is aimed at removing all barriers to trade, finance and procurement, which is tantamount to destroying the system's intricate space-time structure. This inevitably results in the over-exploitation of the poor, especially in third world countries, that will impoverish the whole economic system. But that is not all.

As the global economic system is embedded within the global ecosystem, over-exploitation in the global economy will drive people to use natural resources at unsustainable rates, so that the global ecosystem increasingly fails to renew itself. This leads to diminished input into the economic system so that even more natural resources will have to be harvested, resulting in a vicious cycle that will ultimately destroy both the global economy and the earth's ecosystem.

Economic globalisation, coupled with the overheated financial and money markets and the unequal

terms of trade imposed by rich countries on the poor are all uncompensated positive entropy that has become manifest as global warming. Global warming is an entire conglomerate of correlated changes in the earth's climate and resources, which are causing immense social unrest and upheavals everywhere.

11. Biodiversity and productivity

The model of agriculture promoted by academic science for half a century is high yielding monoculture of the green revolution depending on high inputs: fertilizers, herbicides, pesticides, not to mention water from huge irrigation projects, all of which have done untold damages to the environment, driven small farmers off the land and into poverty and suicide.

The loss of biodiversity from the monocultures of the green revolution is tremendous. Of 7000 species consumed by people, there are 103 species that comprise 90% of the world's food crops, and of those, only three, rice, wheat and maize provide 50% of the calories and 56% of the protein (Thrupp, 1998).

What it used to be like – preserved in, among other places, the Gunung Haliman National Park in West Java, Indonesia – is a wonderful mix of cultivated fields, rice terraces, and forest gardens teaming with life and biodiversity. Biodiversity and productivity go together, as indigenous farmers everywhere on earth have always known.

Academic ecologists have denied or ignored that for a long time. But evidence has been accumulating in ecology that productivity – rate of production of biomass – generally, though not always goes up with biodiversity (reviewed by Ho, 2004a) although the precise causal relationship is still uncertain.

There has been a revival of traditional ecological farming all over the world since the 1980s, which is accompanied by the recovery of indigenous biodiversity and a lot of innovations.

Takao Furano, a Japanese farmer, has perfected an ecological system of rice cultivation in his small farm near Fukuoka in Kyushu (Ho, 2004b). It involves introducing ducklings into the paddy fields planted with the rice seedlings, so they can feed on the insect pests, weed seeds and the golden snail (thus turning pests into resources), aerated the water, provided mechanical stimulation for the rice plants to grow thick and

strong and yield more, make droppings to feed daphnia and other small organisms in the water that feed on the plankton; all of which provide food for the roach. The azolla or duckweed included as part of the system is very efficient in fixing nitrogen; it attracted insects, and is also food for the ducklings. Duckweed is very prolific; doubling itself every 3 days, so it can be harvested for cattle-feed as well. The duckweed spread out over the surface of the water proving hiding places for the fish.

At the end of the year, Furano gets a bumper harvest of 7 t of rice, 300 ducks, 4000 ducklings and countless fish from 1.4 ha of paddy fields. Another 0.6 ha goes to produce organic vegetables that feed 100 peoples beside his family of nine. At that rate, no more than 2% of the population need to farm in order to feed the entire country. This system is perfect, as it does not require any weeding.

Since Furano introduced this one-bird revolution over 10 years ago, more than 10,000 farmers in Japan have taken it up, and it is spreading fast through South Korea, Vietnam, the Philippines, Laos, Cambodia, Thailand and Malaysia. Farmers have increased yield 20–50% or more in the first year. One farmer in Laos increased his income three-fold.

This and other innovations in traditional farming methods have exploded the myths that traditional farming is inefficient and hard work, and small farms are unproductive. But attitudes are beginning to change.

12. Biodiversity provides space-time differentiation for energy storage, which is productivity by another name

Tilman et al. (2001) reported the results of 7 years experiment in the University of Minnesota, St. Paul, testing how well crops do in monoculture plots compared to mixed plots of up to 16 species. They found that plots with more species yielded on average 2.7 times as much as monocultures. Many high diversity plots outperformed the best monoculture plots. And the results got better in successive years.

The above ground productivity or biomass tended to saturate at four species in the earlier years, but kept on improving in later years. The above ground biomass was correlated with below ground biomass increase, so total biomass also went up. That is good news from the

point of view of sequestering carbon dioxide from the atmosphere.

Biodiverse fields produce more and are also better carbon sinks. The effect was mainly due to the number of species planted: the more diverse the plot the greater the productivity. It was not a transient effect, as it improved in successive years, and there seems to be a genuine complementary relationship between the plants either because together they make use of resources better, or they genuinely help one another out.

This work has generated a great deal of debate, mostly because mainstream ecologists really do not believe in ecosystems. They are obsessed with competition, and see only a world in which individuals within a species compete as much as different species compete against one another for space and other resources.

One hypothesis that has been around for a long time is that diversity is ultimately determined by the amount of energy available to an ecosystem (Gaston, 2000). Ecologists have long noticed that while a hectare of tropical rainforest contains some 200–300 species, the same area of temperate forest contains only 20–30 species.

High proportions of land and freshwater species on earth do occur in the tropics, which receive the greatest amount of the sun's radiated energy. The average number of species increases from the poles towards the equator for many groups of organisms including protists, trees, ants, woodpeckers and primates, and for data across a range of spatial resolutions. Species richness also appears to increase with energy, measured as mean annual temperature, and evapotranspiration.

But that does not seem to be the whole story. The relationship between diversity and productivity was found to vary at different spatial scales. At large geographical scales, such as across continents in the same latitude, diversity generally increases with productivity. At smaller local scales (metres to kilometres), this does not hold true.

So, another hypothesis is the heterogeneity of the environment both spatially and temporally (Ritchie and Olff, 1999), which ecologists believe, ameliorates competition, because it allows different species to co-exist in their different environmental niche.

There may be a more fundamental explanation based on the thermodynamic theory of the organism presented here.

First of all, it is not just the amount of radiant energy falling on the ecosystem that determines productivity. It is the energy captured and stored, to make organisms that reproduce, that have life cycles coupled to the energy flow.

Intuitively, one can see that for the ecosystem to capture and store a lot of energy, it has to have a great diversity of organisms and species linked together through energy exchange, and more importantly, with life cycles of different sizes, that grow at different rates. At the bottom, we have bacteria, with very short life cycles, and at the top, giant redwoods that have extremely long life times. Not only are the life cycles of different lengths, species have different spatial distributions. Each species is playing its part in the ecosystem by storing the energy captured from sunlight by green plants.

In the thermodynamics of organised complexity, productivity and the complexity of space-time differentiation – a correlate of biodiversity – are completely linked: the more complex the space-time differentiation, the greater the energy stored, which is productivity by another name.

It also explains why greater energy input does not necessarily increase productivity (Ho, 2004a,c): if the energy is supplied at a rate greater than the space-time differentiation of the system can assimilate, then no further increase in productivity can occur, as seen in the rice production systems. An over-abundant supply of energy can even unbalance the system, leading to a decrease in space-time differentiation (c.f. "eutrophication" in Ulanowicz, 1986), and hence a fall in productivity. That could be relevant to global warming.

13. The myth of constant carrying capacity

These findings also explode the myth of constant 'carrying capacity' that have been used to estimate how many people a piece of land, or the earth as a whole, can support.

In recent years, African farmers all along the edge of the Sahara, in Nigeria, Niger, Senegal, Burkina Faso and Kenya, have been working miracles (Pearce, 2000), pushing back the desert, and turning the hills green, simply by integrating crops and livestock to enhance nutrient recycling, by mix-cropping to increase system diversity, and reintroducing traditional

water-conservation methods to overcome drought. Yields of many crops have tripled and doubled, keeping well ahead of population increases.

In fact, high local population densities, far from being a liability, are actually essential for providing the necessary labour to work the land properly, digging terraces and collecting water in ponds for irrigation, and to control weeds, tend fields, feed the animals and spread manure. In some areas, the population density or carrying capacity went up five-fold, but the land is far more productive than ever before.

Organisms are the most energy-efficient 'machines' by far, a point lost on policy-makers bent on increasing efficiency by getting rid of workers and introducing other unsustainable 'labour-saving' measures. It is high time policy-makers learn thermodynamics.

References

Abrupt Climate Change: Evidence, Mechanisms and Implications. 2003. Royal Society Scientific Discussion Meeting. Royal Society, UK. http://www.rmets.org/pdf/programme.pdf.

Brown, L.R., 2003. Plan B Rescuing a Planet under Stress and a Civilization in Trouble. Earth Policy Institute, W.W. Norton & Co, New York.

Bunyard, P., Ho, M.W., Burcher, S., 2003. Life of Gaia series. Science in Society, 20, 20–33. http://www.i- sis.org.uk/isisnews.php.

Clements, F.E., 1916. Plant Succession: An Analysis of the Development of Vegetation. Carnegie Institute of Washington, Washington, DC.

Corliss, J.B., Dymond, J., Gordon, L.I., Edmond, J.M., von Herzen, R.P., Ballard, R.D., Green, K.K., Williams, D., Bainbridge, A., Crane, K., van Andel, T.H., 1979. Sumarine thermal springs on the Galapagos rift. Science 203, 1073–1083.

Denbigh, K.G., 1951. The Thermodynamics of the Steady State. Mathuen & Co. Ltd., New York.

Fraser, R.A., Kay, J.J., 2002. Exergy analysis of ecosystems: establishing a role for thermal remote sensing. In: Quattrochi, D., Luvall, J. (Eds.), Thermal Remote sensing in Land Surface Processes. Taylor and Francis Publishers, New York.

Gaston, K.J., 2000. Global patterns in biodiversity. Nature 405, 220–227.

Gladyshev, G.P., 1999. On thermodynamics, entropy and evolution of biological systems: What is life from a physical chemists's viewpoint. Entropy 1, 9–20. http://www.mdpi.org/entropy/papers/e1020009.pdf.

Goldsmith, E., 2004. Feeding the world under climate change. Science in Society 24, 34–36.

Hannon, B., Ulanowicz, R.E., 1987. Proc. Roy. Soc., B. Lond. 232, 181–192.

Ho, M.W., 1993. The Rainbow and the Worm, The Physics of Organisms. World Scientific, Singapore.

Ho, M.W., 1995. Bioenergetics. Book Two, S327 Living Processes, An Open University Third Level Course. Open University Press, Milton Keynes.

Ho, M.W., 1997. On the nature of sustainable economic systems. World Futures 51, 199–221.

Ho, M.W., 1998a. The Rainbow and the Worm, The Physics of Organisms, 2nd (enlarged) ed., reprinted 1999, 2001, 2003 (available online from ISIS website www.i- sis.org.uk).

Ho, M.W., 1998b. Are sustainable economic systems like organisms? In: Koslowski, P. (Ed.), Evolution, Development and Economics. Springer-Verlag, Berlin.

Ho, M.W., 1999. Genetic Engineering Dream or Nightmare? Final chapter, Third World Network, Gateway Penang and Bath, 2nd Ed. Gill & Macmillan and Continuum, Dublin and New York.

Ho, M.W., 2004a. Energy, productivity and biodiversity. Science in Society 21, 48–49. http://www.i- sis.org.uk/isisnews.php.

Ho, M.W, 2004b. One bird ten thousand treasures. Science in Society 23, 17–18. http://www.i- sis.org.uk/isisnews.php.

Ho, M.W., 2004c. Why are organisms so complex? A lesson in sustainability. Science in Society 21, 50–51. http://www.i-sis.org.uk/isisnews.php.

Ho, M.W., Lawrence, M., 1993. Interference colour vital imaging – a novel non-invasive technique. Micros. Anal., 26.

Ho, M.W., Haffegee, J., Newton, R., Zhou, Y.M., Bolton, J.S., Ross, S., 1996. Organisms as polyphasic liquid crystals. Bioelectrochem. Bioenerg. 41, 81–91.

Homer, M., Kemp, W.M., McKellar, H., 1976. Trophic analysis of an estuarine ecosystem: salt marsh-tidal creek system near Crystal River, Florida. Unpublished data.

Jørgensen, S.E., 1992. Integration of Ecosystem Theories: A Pattern. Kluwer Academic Publishers, Dordrecht.

Kestin, J., 1968. A Course in Thermodynamics. Hemisphere Press, New York.

Ling, G., 2001. Life at the Cell and Below-Cell Level. Pacific Press, New York.

Luvall, J.C., Holbo, H.R., 1991. Thermal remote sensing methods in landscape ecology. In: Turner, M., Gardner, R.H. (Eds.), Quantitative Methods in Landscape Ecology. Springer-Verlag, New York, Chapter 6.

Matsuno, K., Swenson, R., 1999. Thermodynamics in the present progressive mode and its role in the context of the origin of life. BioSystems 51, 53–61.

McClare, C.W.F., 1971. Chemical machines, Maxwell's demon and living organisms. J. Theor. Biol. 30, 1–34.

Morowitz, H.J., 1968. Energy Flow in Biology. Academic Press, New York.

Thrupp, L.A., 1998. Cultivating Diversity: Agrobiodiversity and Food Security. World Resources Institute, Washington, DC.

Tilman, D., Reich, P.B., Knops, J., Wedin, D., Mielke, T., Lehman, C., 2001. Diversity and productivity in a long-term grassland experiment. Science 294, 843–845.

Odum, E.P., 1969. The strategy of ecosystem development. Science 164, 262–270.

Odum, H.T., 1971. Environment Power and Society. Wiley, New York.

Pearce, F., 2000. Desert harvest. New Scientist, 44–47.

Ritchie, M.E., Olff, H., 1999. Spatial scaling laws yield a synthetic theory of biodiversity. Nature 400, 553–560.

Rosen, R., 1991. Life itself: a comprehensive inquiry into the nature. In: Origin and Foundation of Life. Columbia University Press, New York.

Ross, S., Newton, R., Zhou, Y.M., Haffegee, J., Ho, M.W., Bolton, J.P., Knight, D., 1997. Quantitative image analysis of birefringent biological material. J. Micros. 187, 62–67.

Schneider, E.D., Kay, J.J., 1994. Life as a manifestation of the second law of thermodynamics. Math. Comput. Model. 19, 25–48.

Schrödinger, E., 1944. What is Life?. Cambridge University Press, Cambridge.

Ulanowicz, R.E., 1983. Identifying the structure of cycling in ecosystems. Math. Biosci. 65, 210–237.

Ulanowicz, R.D., 1986. A phenomenological perspective of ecological development. In: Poston, T.M., Purdy, R. (Eds.), Aquatic Toxicology and Environmental Fate, vol. 9, ASTM STP 921. American Society for Testing and Materials, Philadelphia, PA, pp. 73–81.

Ulanowicz, R.E., 1997. Ecology, the Ascendent Perspective. Columbia University Press, NY, 201 pp. ("Centripetality" first cited on p. 47).

Ulanowicz, R.E., 2001. Ludus Vitalis 9, 183–204.

Ulanowicz, R.E., 2003. Some steps towards a central theory of ecosystem dynamics. Comput. Biol. Chem. 27, 523–530.

Ulanowicz, R.E., Ho, M.W., 2005. Diagnostic indicators of ecosystem health, in preparation.