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54

Interdependence of Biodiversity and Development Under Global Change

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Interdependence of Biodiversity and Development Under Global Change

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Cover photos (top to bottom): Agro-ecosystem used for thousands of years in the vicinities of the Mycenae palace (located about 90 km south-west of Athens, in the north-eastern Peloponnese, Greece). In the second millennium BC Mycenae was one of the major centres of Greek civilization (photo P. Ibisch).

Modern anthropogenic urban ecosystem dominated by concrete, glass and steel materials (London City Hall, Great Britain) (photo P. Ibisch).

Undernourished child in deforested and desertified inter-Andean dry valley ecosystem (between La Viña and Toro Toro, northern Potosí, Bolivia) (photo P. Ibisch).

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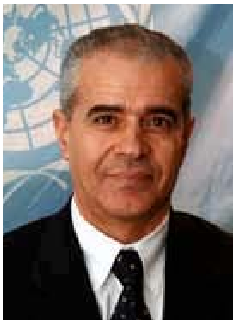


At its second meeting, held in Jakarta, November 1995, the Conference of the Parties of the Convention on Biological Diversity adopted the ecosystem approach as the primary framework for action under the Convention. The Ecosystem Approach recognizes that humans, with their cultural diversity, are an integral component of ecosystems. This has been known for a long time, but it has yet to be internalized by the whole society to assure present and future human survival.

Our modern civilization experiences—due to increased urbanisation and compartmentalised knowledge—an increasing alienation from nature obscuring common understanding of our real dependence on biodiversity and ecosystems. The complex global economy interwoven with a worldwide financial architecture has obscured the fact that all these human systems remain nested as sub-systems in the broader Earth eco-system. Humans and everything we create by using natural renewable or non renewable resources is subordinated to the general laws of nature that rule the functioning of this unique Earth system. Even though we are just a sub-system, human resource use driven by an ever accelerating growth and globalization of societies' activities has the power to catalyze irreversible degradation of the global ecosystem compromising human well-being and maybe even the existence of our civilization. As the Global Biodiversity Outlook 3 (GBO3) points out we are rapidly approaching critical tipping-points of life-supporting systems, if we don't break business as usual attitudes and habits.

Rediscovering the insights of these risks, the current technical series explores the manifold interrelations and interdependencies between biodiversity and human development. Applying system theory and through a transdisciplinary analysis of bio-cultural evolution, concrete up-to-date case studies and global statistical correlations this technical series goes deeply into the root-causes and drivers of environmental degradation and biodiversity loss. It shows that understanding the role and value of biodiversity and ecosystems for human well-being is more than ever a crucial pre-requisite and vital question for new and urgent needed development paradigms. In line with other initiatives like TEEB, IPBES or the Green Economy, among others, the technical series explores appropriate means and ways to translate proven knowledge and open questions into policy-relevant messages.

To find real solutions to both preserving biodiversity and securing sustainable development for the future in times of global socio-economic and environmental change, the authors of the technical series present and call for an in-depth understanding and comprehensive application of the CBD ecosystem approach. This requires to shift away from merely treating the symptoms of the biodiversity crisis. Following a precautionary approach, both knowledge and uncertainties should strategically be factored into decision-making to preserve the interests of current and future generations. New management systems for production, consumption for the global economy needs to be developed through a much more proactive management and by mimicking natural systems.

We are pleased to introduce this volume of the Technical Series of the Convention on Biological Diversity as a very useful contribution and enrichment of the debate on new paradigms for sustainable development in harmony with nature that actually move the agenda of committed scientists, policymakers and practitioners worldwide.

Dr. Ahmed Djoghlaf
Executive Secretary
Convention on Biological Diversity

B. Background papers

B.2 THEORETICAL BACKGROUND PAPERS

B.2.1 AN ALTERNATIVE CONCEPTUAL FRAMEWORK FOR SUSTAINABILITY: SYSTEMICS AND THERMODYNAMICS

Peter Hobson & Pierre L. Ibisch

ABSTRACT

The conventional view held by many scientists was that a thorough understanding of nature in all its diversity and complexity could best be achieved by an ever increasing detailed analysis of its single pieces, in other words, adopting an atomistic approach to the study of the individual components within a system, and by observing cause-effect behaviour between them. However, such technomorphic reductionism does not factor in emergent properties of systems, variability and non-linear processes across scales, which leads to problematic misunderstandings. In this paper, a systemic approach to sustainability is developed setting out some of the philosophy and science underpinning current understanding of complex systems and thermodynamics. Ecosystem theory, based on systems theory and ecosystem thermodynamics, facilitates a better understanding of the relationship between natural and anthropogenic systems. It also sets out clear parameters and measurable boundaries to systems in terms of productivity, carrying capacity, limits of change, resilience, as well as factors in the unpredictable nature and uncertainty of system behaviour. Systems, to a certain extent, are open to both energy and material flow but continue to maintain definition and integrity in rather the same way as does a cell with a permeable membrane. A central feature to systems ecology is the transformation of energy through and across system-scale boundaries of ecosystems, encompassing thermodynamics, chemistry, and both biological and ecological energetics.

Structure and function of complex systems are defined by an ‘uneasy’ relationship between apparent chaotic events and self-ordering constructs. The resulting uncertain and unpredictable performance of natural systems requires a post-normal approach to analysis and management. However, in a global society increasingly governed by (cost-)efficiency, predictability, measurable targets and informed practice there is very limited scope for building ‘post-normal’ science into mainstream policy and practice. Sustainability defines the single or multiple states of dynamic equilibrium—the ultimate ‘gravitation’ of systems towards attractor basins. Any external gradient that causes fundamental shifts in a system, enough to create a hysterisis effect, will inevitably bring about destabilization and loss of sustainability. Functional and evolving systems that are able to return or shift to operating points without losing fundamental and typical emergent properties develop sustainably. However, sustainability does not imply a maintaining of the status quo, but may describe a system undergoing a building phase towards complexity through the increasing evolution of sub-systems (attractor basins) or indeed shifts in meta-state of existing attractor basins. A complex system is organised hierarchically with nested adaptive cycles working to feedback mechanisms.

Thermodynamic efficiency seems to be the major driver of system organization and evolution. Evolution could be defined as a process that, under the physical laws of nature, produces systems, which are able to self-organize, multiply, reproduce themselves and diversify at the cost of increasing entropy in other systems. This leads to increasing opportunities of interactions between systems and corresponding complexification of systems of ever higher order. In the global ecosystem, the role of biodiversity in maintaining dynamic equilibrium in complex ecosystems is fundamental and cannot be undervalued. A system is likely to shift towards improvements in matter recycling and increases in information. This process of internalising and re-cycling energy and matter transference (self-ordering) reduces the exchange of materials across borders between systems and this has advantages of retarding the lowering of energy

flux and increasing energy-efficiency. Thermodynamic efficiency can be taken as a measure of system sustainability in terms of auto-regulating the system and maintaining it at in a certain operating point. As a consequence of the dramatic transformation of natural ecosystems to cultural landscapes, the Earth system is losing its resilience and capabilities to dissipate energy, there is less biomass storage in the system, and dissipative structures are undergoing simplification. During the very brief period of civilization the advances of technology have created a false sense of limitless resources and opportunities.

Society has been tricked into thinking that both science and technology are able to skip round problems of energy and material shortages, and that there is ultimately an answer to the dilemma of energy-exergy-entropy. For too long civilization has been living through the myth that laws can be broken and re-written, and under this false sense of security society continues to be driven ever forwards beyond the limits of nature's boundaries.

"*Previously the discourse was about a single machine, or reaction, or discrete phases; now it concerns structures, cycles, systems, and feedbacks (positive as well as negative): complex wholes with their own histories and even explicit anthropocentric evaluations. The term 'system' has become indispensable, as it conveys something about the sort of complexity that is not mere complication or confusion*" (Funtowicz & Ravetz 1997).

If we look for a general blueprint that explains the composition and relationships between all living and non-living components that make up the world, a common theme is apparent, across all scales, namely, the phenomenon of interaction between different elements. These relationships that are governed by boundary-maintaining entities or processes result in the emergence of increasingly complex constructs that can be defined as *systems* (Laszlo & Krippner 1998). The interaction of system components can be of different nature, but always involves the exchange of energy, material and/or information. This apparent 'open' exchange of material and energy suggests that there exist in a system multiple pathways of influence between the diversity of components that ultimately leads to a certain level of self-organization. For instance, in a solar system the various sized bodies that include planets, moons, asteroids, and dust and gas particles influence each other by gravitational energy causing regular rotations and movements around a central star. In a biological population the individuals exchange information and matter, e.g. in the form of gametes and DNA that influences the pattern, structure, behaviour and ultimate survival of the larger construct—the population. Similarly, in social systems such as a political party, a non-government organization, or a community-based action group the members often operate to principles of informed complex networks—so-called "shadow systems" (Stacey 1996), exchanging information in the form of ideas and arguments. In all kinds of systems the interaction does not only lead to a more or less temporary boundary-maintaining process, but also implies that this complex entity is characterized by *emergent properties* that cannot be explained by the collective description of the character and behaviour of each individual component.

Concepts of systems have been around for centuries, but the emergence of a coherent theory that unites several ideas into a single thesis was developed during the 1940s and 50s as a result of the works of several key researchers, von Bertalanffy, Rapoport, Boulding, Ashby, Mead, Bateson and Churchman, among others. Around this time the *Society for General Systems Research* was established, and by 1950 Bertalanffy had his paper on "*An Outline for General Systems Theory*" published in the *British Journal for the Philosophy of Science*, Vol 1, No. 2. Later, in 1968, von Bertalanffy produced a detailed thesis of his work in a book, titled "*General system theory: foundations, development, applications*" in which he defined the term systems theory. His intention was to widen the concept of biological and mathematical systems to apply to all systems in general. By the 1940s and 1950s the combined works of Wiener, Ashby, von Neumann and von Foerster had provided a theoretical and mathematical framework for concepts of complexity, self-organisation and adaptive systems. The collective efforts of these various scientists working on the same theme but in different disciplines contributed towards the development of a 'supertheory' (Luhmann 1987), initiating new scientific approaches and influencing historical-political decisions (Becker 2004). According to a *systemistic* worldview, everything, whether concrete or abstract, is a system or part of a system, and systems have emergent properties that are not observed in the separate components. Thus, any problem that is manifest in the emergent properties of a system should be approached in a systemic way rather than in isolation (Bunge 2000).

In this paper, a systemic treatment of the concept of sustainability is developed. The thesis also builds on the understanding and findings of other authors who have already claimed that a systemic perspective on the nature-society continuum provides a clearer frame of reference for effective analysis, and a more appropriate basis for understanding the urgent problems we face on Earth (e.g., Kay 2008, Kay & Boyle 2008). Accepting the premise that all environmental and social constructs are systems or part of a system, then where components are observed to interact and form systems, a logical question would enquire about the nature of the force that drives systems towards assembling and self-organizing. This question has, in part, been answered through on-going research into thermodynamics. However, rather less is understood about the relationships between the environment, rapidly evolving social systems, and the concept of sustainability in the context of both thermodynamic and non-equilibrium thermodynamic sciences. This paper explores the application of principles and concepts of non-equilibrium thermodynamics to problems of environment—culture relationships and sustainability.

While the post-normal and transdisciplinary concepts related to systemics and thermodynamics have stimulated and enriched general sustainability science, we feel that they have not sufficiently been introduced into biodiversity conservation and the discourses related to the implementation of the Convention on Biological Diversity. Just as systemics provides general explanations for the function and dysfunction of both biological-ecological and cultural entities, it is also the necessary means of carrying out the analysis of interlinkages between biodiversity and development.

B.2.1.a SCIENCE, THE ORIGINS OF SYSTEMS ECOLOGY, AND "THE ORDER OF THINGS"

Life on planet Earth is made up of an extremely complex combination of elements that coalesce and bond to form compounds at the molecular scale which in turn, organise themselves into recognizable shapes and forms at incremental scales of higher magnitude. The final result is the formation of seemingly stable complex constructs that make up the diversity of life forms, from the simplest of organisms to the emergence of immense biomes that cover the surface of the planet. This perception of a hierarchical "nature" has been the subject of intensive and increasingly more sophisticated scientific study through the centuries, and has included the works of Plato, Aristotle, Copernicus, Galileo, Ficino, Odum, and Patten, amongst others. The early conceptual frameworks that included the works of Ficino and Descartes, and more specifically the mechanistic clock analogy (see Leibniz-Clarke correspondence), adopted an intuitively mechanistic understanding of nature as a construct of mechanical components and their manifold 'gears' working together in a predictable way. The dramatic advancement made in science and technology in the late 19th and especially 20th century gave rise to the development of a constructivist-technomorphic base paradigm that worked towards an improved understanding of both nature and social complex systems such as organizations (Malik 2008). Even (conservation) biologists were using technomorphic metaphors, such as the famous rivet-popper hypothesis (Ehrlich & Ehrlich 1981), comparing the species of an ecosystem with constructive parts of an airplane. Similarly, in a more recent publication in Science (Baliga 2008), the processes and functions of a cell were explained using a gear metaphor. The underlying principle to the constructivist-technomorphic paradigm is that the design and construction of nature is based on the assemblage of all its parts that collectively contribute to the purposeful function and adaptation of the whole system.

The conventional view held by many scientists was that a thorough understanding of nature in all its diversity and complexity could best be achieved by an ever increasing detailed analysis of its 'components and gears'. This philosophy also proposed that nature existed in balance and order, working to predictable

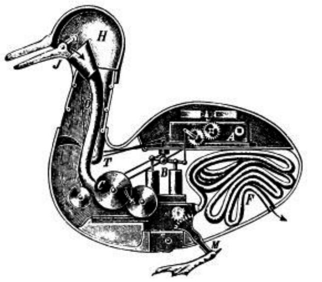
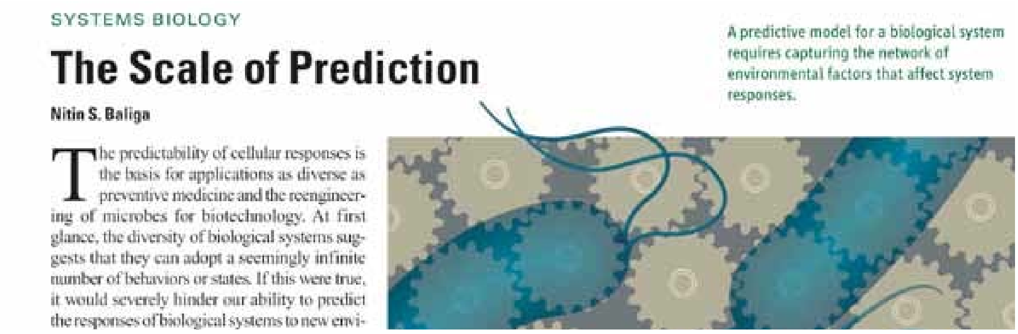


FIGURE 1: Technomorphic view of nature in the 17th and 18th century: Illustration of the automatic duck by Jacques de Vaucanson (1783). The efforts to build functioning mechanic animals is in line with Descartes' view on nature who argued that the physical structure and function of all none-human animals could be explained through reductionist principles and described as "automata".



SYSTEMS BIOLOGY

The Scale of Prediction

Nitin S. Baliga

A predictive model for a biological system requires capturing the network of environmental factors that affect system responses.

The predictability of cellular responses is the basis for applications as diverse as preventive medicine and the reengineering of microbes for biotechnology. At first glance, the diversity of biological systems suggests that they can adopt a seemingly infinite number of behaviors or states. If this were true, it would severely hinder our ability to predict the responses of biological systems to new envi-

FIGURE 2: Example of technomorphic illustration and explanation of systemic processes in living organisms (extract from Baliga 2008).

patterns of behaviour (Wu & Loucks 1995). A logical extension to this idea was that constructs of nature evolved along predictable linear pathways towards higher levels of order and complexity that finally gave rise to a phase of stability—a mature kinetic state. In the first half of the 20th century, Clement's model for vegetation succession from bare earth to climax community, was held up by many ecologists as a fine example of this phenomenon. These predictable models also provided convenient metaphors and much needed evidence to justify practices in environmental management and rural land use practice including agriculture, forestry and landscape design. In all cases it offered the necessary verification for maintaining the status quo or 'fast-tracking' nature to create an instant desired state. This school of science was institutionalised across the western world and provided the underpinning theory to much of human activity and development including mechanistic environmental and conservation practices. Many of the principles and processes recognised in this strand of science continue to be practiced today despite fundamental shifts in scientific understanding of the unpredictability and indeterministic tendencies of nature. Modern cultural landscapes represent spatial analogies of the equilibrium-based scientific philosophy. For instance, agriculture operates to 'grid lines' of utilizable cropping land that is fixed in space and managed on tight, predictable cycles or rotations. Similarly, urban design and planning relies on permanency in order to function within and across space. Often, the same approach is adopted by biodiversity conservation for more natural landscapes despite the unpredictable patterns and behaviour of nature. A common strategy is to first organise biodiversity features according to predetermined categories and then prioritise them using measures of importance and value. Once notified they become fixtures in space and time—targets for clear and unambiguous management objectives that promote the status quo (Hobson 2004). Any shift in the status of these targets away from expectations of conservation value or quality triggers a management response to restore the feature back to favourable status. The myths and assumptions that prevail in the corresponding ***equilibrium paradigm*** are that nature can be corrected, 'fixed', restored, steered, constructed and maintained indefinitely using prescriptive management based on scientific evidence. These principles resonate with Clementsian ideas of sere stage development and final static states of equilibrium. There is little consideration of scale-dependent dynamics, emergent properties and indeterministic tendencies of nature.

THE EMERGENCE OF 'NEW' THINKING ABOUT SYSTEMS

By the beginning of the twentieth century Clementsian ideas of nature as a superorganism, and more specifically, vegetation dynamics operating to linear patterns towards a steady state climax community occupied many themes in ecology. Despite criticisms of his theory by eminent ecologists, such as Henry Gleason and Arthur Tansley and later Robert Whittaker, significant Clementsian views persisted up to the end of the twentieth century. By the 1960s this view was more comprehensively challenged by the emergence of "*systems ecology*" which revolutionised the way scientists thought about the natural world. Leading ecologists including Odum (1983, 1994a), van Dyne (1966), or Patten (e.g., 1978) believed that physical and biological elements in ecosystems could be modelled using principles of cybernetics and computer simulation. A central feature to systems ecology is the transformation of energy through and across system-scale boundaries of ecosystems, encompassing thermodynamics, chemistry, and both biological and ecological energetics. This perception of the natural world was developed further by Odum who introduced the concept of holism and the "macroscope" of ecosystems science. The theme of "macroscope" and holism was encapsulated in the work carried out by scientists in the late 1960s and early 1970s as part of the International Biological Programme (IBP). The objective of this ambitious programme was to amass data on species, energy and material flows, food chains and trophic structures for deciduous and coniferous forests, grasslands, and tundra biomes. Ultimately, complex systems models were generated to study the effects of disturbances and human impacts. However, this particular aspect of the programme failed due to the unforeseen complexities and relationships encountered in ecosystem dynamics and function.

Despite this set-back scientists had started a new generation of complex systems thinking that made significant headway in the use of modelling in ecology, and also in the way that ecosystems were studied. The first attempt made to apply systems ecology in such a way that described planet earth as a single self-regulating complex system was in the highly popularised but controversial Gaia Hypothesis proposed by James Lovelock (1987; compare Lenton 1998, Godderis & Donnadieu 2009). The regulation of the biosphere by living organisms was likened to homeostatic mechanisms in organisms and cybernetic controls in automated machines—a "*cybernetic system with homeostatic tendencies*". Although this idea drew on elements of mechanistic thinking, it presented a fundamental shift away from the perception of perfect balance in nature, as the principle of homeostasis or negative feedback dynamics implied constant change. In fact, ecosystems were believed to be perpetually out of balance and under the influence of indeterministic disturbances. The Gaia hypothesis has contributed towards a better understanding of the relationship between complex systems theory and global ecology and this in turn has provided society with a more sophisticated description of an Earth as a complex system subjected to periods of uncertainty and indeterministic tendencies.

Recognisable landscapes and systems in nature and society, such as mires, forests, savannahs and traditional pastoral cultures appear to be stable but can suddenly shift and establish themselves as something new. This 'regime-changing' phenomenon can occur because of complex interactions within a system that have influence across scales. Small, localized interactions serve as sources of adaptation and events that feed up to higher levels of organisation, and conversely, large-scale emergent constructs exert constraint on the behaviour and states at smaller scales (Kinzig *et al.* 2006). This 'uneasy' relationship between apparent chaotic events and self-ordering constructs defines the structure and function of complex systems, and in nature, is the source of diversity. However, there is a real dilemma with this strand of science that makes for uncomfortable relationships with both policy makers and managers. The irreducible uncertainty of complex systems complicates efforts to design either experiments or models that provide unequivocal or predictable evidence in the way that traditional 'normal' science based on more Newtonian principles is able to do. Consequently, in a global society increasingly governed by (cost-)efficiency, predictability, measurable targets and informed practice there is very limited scope for building 'post-normal' science into mainstream policy and practice. The more 'reliable' and predictable problem-solving methods and outcomes of reduction science prevail in policy and the wider social environment. This is despite growing support for non-equilibrium ecology and complex systems theories helped by recent research into problems of climate change. This situation has rather less to do with differences in schools of thought in the science world and is more about the relationship between science and policy. Modern constructs of society and economics rely on predictions, certain 'guarantees' of stability in socio-economic and environmental systems to the extent that it promotes self-fulfilling experimentation and modelling. In other words, you validate your actions rather than generate probabilistic scenarios that force you to take decisions based on 'best case scenario' and risk aversion.

COMPLEX SYSTEMS AND POST-NORMAL SCIENCE

Characteristically, reductionism decomposes a system into pieces and then attempts to understand how the system works by adding them together and observing cause-effect behaviour between them. It does not factor in emergent properties of systems, variability and non-linear processes across scales. In this example a predictable, mechanical operation would only occur if the different components within a system were not allowed any freedom at all (Allen 1990). Alternatively, a *post-normal* science (Ravetz 1986, Funtowicz & Ravetz 2008) such as complexity science, has widened the vocabulary used in science by offering more appropriate narratives and metaphors to explain the patterns and functions of systems. The intelligence and learning in complex systems come from within—intercausative, rather than from outside and looking in (Allen 1990). Through this more enlightened approach scientists have begun the process of describing in detail the character and behaviour of ecosystems in terms of complex systems.

Complex systems are hierarchical constructs made up of systems nested one inside another at different levels, the ***holons***[42]. Energy and material flow not only occurs across scales between these different levels but also from outside the system (Kay 2008). This idea proposes that systems, to a certain extent, are open to both energy and material flow but continue to maintain definition and integrity in rather the same way as does a cell with a permeable membrane. The cell model might help explain how systems are able to operate to negative feedback processes as well as self-regulate and order themselves. A system without definition or structure would collapse into a state of chaos under the influences of stressors. The processes and dynamics operating in a system are typically non-linear and are self-reinforcing, creating emergent properties and leading to self-organisation. Catastrophic behaviour, moments of unpredictable change, are the norm, leading to irreducible uncertainty. Despite the unpredictable nature of systems, self-ordering is possible through feedback loops that are responsible for autocatalytic cycling of materials and energy rather than as a result of linear causal mechanical factors. A consequence of this phenomenon is that complex systems strive for optimum status rather than minimum or maximum, and that there may not necessarily be an equilibrium point or a preferred state for the ecosystem. Rather there may be multiple steady states, none of which is the 'right' one (Kay 2009). The actual state an ecosystem occupies is a function of its history (Kay 2000). The principle of 'meta-states within states', a heterogeneous system, is the possible source of resilience and equilibrium that contributes to the systems' sustainability.

As well as being holarchic, systems also organise and maintain themselves at **'attractors'** by feedback loops (Schneider & Kay 1994). Within a defined '**attractor basin'** a system will appear to be in an equilibrium state. However, there can be more than one attractor in a system as there may not be an ecologically preferred state. When gradients are applied (these define a 'force of environmental change' such

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[42] The concept of holonics was suggested by Arthur Koestler (1967; compare Koestler and Smythies 1969); the term holon implies that the world consists of parts which are a relatively autonomous whole (= hol-) while, at the same time, being a part (= -on) of something larger. "Parts and wholes in an absolute sense do not exist in the domains of life. The concept of the holon is intended to reconcile the atomistic and holistic approaches. (…) More generally, the term "holon" may be applied to any stable biological or social sub-whole which displays rule-governed behaviour and/or structural Gestalt-constancy. Thus organelles and homologous organs are evolutionary holons; morphogenetic fields are ontogenetic holons; the ethologist's "fixed action-patterns" and the sub-routines of acquired skills are behavioural holons; phonemes, morphemes, words, phrases are linguistic holons; individuals, families, tribes, nations are social holons" (Koestler 1969).

as pollution), to a system and move it from its equilibrium position, it will respond by attempting to dissipate or degrade the effects of the disturbance in order to maintain its state within the attractor basin (Baldwin *et al.* 2004a). Furthermore, other attractors may also emerge in the system that contribute to the degradation and dissipation of the effects of the gradient (Baldwin *et al.* 2004a). As more of these sub-systems, each within their own attractor basins, emerge the 'super-system' develops complexity and self-organising tendencies. This phenomenon again, describes the spatio-temporal heterogeneity of a system and depicts the emergence of dissipating structures at different scales in response to a stressor. The growth in sub-systems leads to increasingly more complex landscapes with multiple systems of similar ecological states at any one time. Incremental change in the gradient or 'stressors' does not necessarily elicit incremental change in an ecosystem. More typically, the ecosystem may appear unaffected and continue to function as before. A system is able to maintain stability by self-organising and developing internal structures—diversity of form and function, the very stuff of biodiversity. Over time self-organising processes result in the emergence of certain key characteristics including stable dissipative structures (complex cycles and diverse, representative species); the growth of the physical-biological structure (biomass); growth in complexity of the network between the components; and growth of 'information' (increase in the proportion of more complex organisms with K-strategy to those with r-strategy) (Jørgensen 2006).

The position of a system within its attractor basin is defined by a threshold (May 1977). Systems that flip over this threshold—the '***tipping point***', can shift between attractors and can thus re-organise themselves around new attractors (states). However, once the threshold is reached then a small external 'force' can cause dramatic, irreversible change to the ecosystem (Kay 2009). The threshold of a system represents a boundary of 'tolerance'; it helps to define the functional integrity of the system. Thresholds also create distinction between the dynamics operating from within a system and external forces or gradients that may operate at different levels of magnitude and frequency. There are boundaries either side of threshold points that signify levels of unstable equilibrium between regimes. These 'precarious' zones represent the capacity for resilience in a system, that is, the ability of a system to absorb disturbance and still retain essentially the same function, structure, identity and feedbacks (Walker *et al.* 2006). Both changes in ecological conditions and management practice can determine whether a system crosses thresholds, and a regime shift represents a loss of resilience, in which existing structures, functions and feedbacks give way to new ones. During such an event, the hierarchical structure of systems suggests that multiple thresholds across scales of space and time are crossed, essentially, a cascade effect, that can create change in ecological, social and economic domains. The new emergent regime has the characteristic of being highly resilient and resistant to natural recovery or to attempts through management to restore the original system. Regime shifts are not just the result of interactions occurring within a particular domain but can happen because of interactions across ecological, economic and social domains (Carpenter & Brock 2004).

The findings of the Millennium Ecosystem Assessment presented a stark picture of declining ecosystem functionality across almost the entire planet. What is meant by loss of functionality? It refers to the functioning that enhances the ecosystem's adaptive capacity and reduces the risk of abrupt and dramatic change. If the explanation for ecological thresholds is used to describe this loss, then we can expect to approach a tipping point at which the Earth's systems undergo a dramatic and irreversible change (Lyytimäki & Hildén 2007, Rockström *et al.* 2009a, b). The cause for much of this decline of functionality, and the ultimate switch of ecosystems to new states is due to various anthropogenic pressures (Walker & Meyers 2004). Human-generated systems and disturbance regimes have introduced novel structures and feedback loops within and between ecosystems, often through management practices that operate to objectives of maintaining the status quo or facilitating smooth change (Lyytimäki & Hildén 2007). The consequences of a regime shift are difficult to predict as they rarely if ever result in a linear shift from one state to another; rather, they often generate possibilities of several alternative states and points of no return.

The complex nature of system structure and dynamics complicates attempts to distinguish between non-linear processes or stochastical events (Matius *et al.* 2006). It is difficult to establish the degree of force or strength of gradient that results in regime shift in systems. In fact, there are problems with singling out any one stressor from the number of likely interacting factors that triggers an abrupt change in ecosystem quality. Attempts to understand human-induced regime change is further confounded by poor definitions of system thresholds (Groffman *et al*. 2006). In the examples of badlands all over the world with degradation of land and soils, it is possible to present a scenario based on the principles of complex systems theory. Certainly, we can demonstrate the application of system hierarchy and cascade effects and feedback loops between meta-systems. For instance, the loss of biodiversity over time can also represent a loss of photosynthesis and subsequent loss of biomass. This in turn, affects carbon sequestration, soil organic matter and ultimately, soil structure and composition. Resulting changes in soil conditions will affect water and nutrient retention and capacity. Inevitably, both the nutrient cycling and hydrological regime will suffer as a result, finally, leading to ecosystem dysfunctionality or even collapse.

Theoretical problems of the kind just described can lead to ambiguity and confusion amongst managers and policy makers. Understandably, practitioners would prefer to work with prescriptive models that demonstrate tangible outcomes. What has emerged in the last two decades is a divergence between a body of science and practice that holds to principles of reductionism and prescriptive management, and a growing school of thought that embraces a post-normal approach that is more familiar with fuzzy logic and adaptive management of uncertain and unpredictable complex systems. In ecological science and its application we find even a 'hybrid approach': on the one hand, complex systems are carefully modelled, amongst others taking into account non-evidence-based scenarios. On the other hand even some system scientists believe that they just need to produce models that are sufficiently complete and sophisticated in order to predict future systems' performance. Actually, to some extent both philosophies, normal and post-normal, are applied in global policy and practice. However, this in turn can also create incompatibilities and confounding problems that contribute to the ongoing decline of ecosystem functionality and diversity. For instance, in working models for sustainable development, outcomes are based on agreed compromises between social, economic and environmental interests rather than on a unifying principle of a fully integral complex system. This partisan approach perpetuates competition for resources between the three domains, all the while claiming the moral high ground through demonstrable efforts towards conflict resolution. More effective models for sustainable development are needed that attempt to build a practical framework around theoretical concepts (see below).

THE ADAPTIVE CYCLE AND PANARCHY: AN APPROPRIATE MODEL DEPICTING COMPLEX SYSTEMS

The adaptive cycle first proposed by Holling (1986) and later refined by both Holling and Gunderson (Gunderson *et al.* 1995, Gunderson & Holling 2002) provided an elegant conceptual model for a complex system that is operating to both indeterministic and self-organising behaviour. This metaphor provides a convenient framework for our understanding of the state, dynamics and functionality of a system. Furthermore, it complements the previous model, attractor basins, by completing the basic description of a complex system. The attractor basin provides us with a spatial model—the ecosystem landscape or horizontal plane, whilst the adaptive cycle offers the scale-dependent functional character of a system—the vertical plane. Biological and socio-economic systems, appear stable at certain periods of their lifecycle until an event shifts them into a brief period of chaos. What then follows is a more protracted period of recovery through a process of self-organising that can either lead to some measure of re-semblance towards the original state or to the emergence of a new system. The complex nature of a system is manifest not just in the connections within but also the linkages and relationships that occur across scales. A complex system is organised hierarchically with nested adaptive cycles working to feedback mechanisms. Together they form a ***panarchy***[43]. The panarchy describes how a healthy system can evolve and adapt, thus creating opportunity while being kept safe from other systems that otherwise might destabilize it because of their nature and higher energised state. Each level is allowed to operate at its own pace, protected from above by slower, larger levels but invigorated from below by faster, smaller cycles of innovation. The adaptive cycle model identifies four distinctive phases in a system, which are destruction, reorganization, growth and conservation (Gunderson & Holling 2002). Together these phases unite system organization, resilience, and dynamics. An adaptive cycle that alternates between long periods of aggregation and transformation of resources and shorter periods that create opportunities for innovation is proposed as a fundamental conceptual model for understanding complex systems from cells to ecosystems, and more recent interpretations of the structure and function of human societies. The four phases of the adaptive cycle are:

- growth or exploitation (r)
- conservation (K)
- collapse or release (omega, 'Ω)
- reorganization (alpha, a).

Of the two major phases (or transitions), the first, often referred to as the 'foreloop', from r to K, is the slow, incremental phase of growth and accumulation. The second, referred to as the 'backloop', from Omega to Alpha, is the rapid phase of reorganization leading to renewal. During the slow transition from exploitation to conservation, stability and connectedness in an ecosystem increases, contributing to an accumulation and storage of nutrients and biomass. Competition between species leads to a relatively small number of them becoming dominant whilst the remaining majority are much reduced but retained in scattered clusters across the patchy landscape. Long periods of 'maturity' can lead to systems becoming over-connected and brittle, a state in which collapse or revolt (Ω phase) can occur. This is typically a short transitional period that rapidly moves into the next phase of reorganisation (α) in which the system slowly regains organisation that was lost in the revolution.

The hierarchical organisation of adaptive cycles across space and time helps scientists to understand and explain how systems can briefly generate novel recombinations. These narrow windows of events open briefly, but the outcomes of these disturbances do not normally trigger cascading instabilities of the whole 'panarchic complex' because of the stabilizing nature of nested holarchies. In essence, larger and slower components of the holarchy provide the 'memory' and legacies of the past to allow recovery of smaller and faster adaptive cycles.

HOW DO WE NOW APPLY THE MODEL OF PANARCHY TO THE CONCEPT OF SUSTAINABLE DEVELOPMENT?

Failed attempts, so far, to construct a working anthropocentric model for sustainable development point to tensions between nature and culture, and are manifest in the conflicting interests emerging from a growing and developing global society. It is less likely to be a result of deficiencies in science and technology. Furthermore, attempted resolutions to this dichotomy often represent flawed strategies of avoiding contradictions (Proctor 1998). The nature-culture antagonism that expresses modern man's approach to his natural environment is a complex manifestation of an essentially simple principle centred on the exploitation of natural capital to service socio-economic advancement. Unlike early hunter-gatherer communities, modern-day society has de-coupled itself from nature, a transition that has largely come about through advances in technology (see Ibisch & Hobson, B.2.2., in this document). Technocentrism is now the norm that defines and drives culture, thus re-enforcing perceptions of the externalization of nature in concept and practice (Haila 2004). Prolonged human impact that prevents an ecosystem from

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[43] Panarchy: a form of governance (-archy; suffix meaning "rule," from Latin -archia, from Greek -arkhia, from arkhos "leader, chief, ruler," from arkhe "beginning, origin, first place") that would encompass (pan-; prefix meaning "all, whole, all-inclusive," from Greek, combining form of pas [neut. pan, masc. and neut. gen. pantos] "all", all others). It was first used in a socio-economic context by de Puydt (1860).

returning to equilibrium will result in a break-down in energy-dissipative properties, and a shift from complex self-organising structures to more simple and inefficient systems. In this scenario an increase in positive feedback mechanisms and inefficient energy loss (leaky systems) will hasten an ecosystem towards comprehensive collapse. The scale of human impact on the natural world forces a reappraisal of post humanist perspectives, which reject the ontological separations of nature and culture (Braun 2004, Franklin 2006, Haila 2000).

To develop a better understanding of sustainability and to build frameworks for good practice, both policy and management need an appropriate template and reference point. The use of reference sites is a widely accepted practice in ecological studies and in environmental restoration programmes. The term defines an ecosystem or landscape that is either "free-willed" or unaffected by human disturbance. In reality there are very few examples of untrammelled ecosystems remaining across the globe. Furthermore, it is philosophically debatable whether human-free landscapes provide a realistic representation of the natural world of today. However, it is possible to agree on a definition that recognises an ecosystem that is functioning according to the internal forces of the system and is not in any way modified or engineered by human design or activities. Examples of unmodified ecosystems can still be found in the more remote parts of the World. Some of these have provided appropriate sites for the study of ecosystem function and dynamics.

COMPLEX SYSTEMS THEORY, BIODIVERSITY AND SUSTAINABILITY

Evolution—the starting point: More recently, theories about systems complexity and hierarchical levels of organisation ranging from genomic systems to macro-scale ecosystems have been used in attempts to explain Darwinian evolution (Winther 2008). The central tenant to ***'systemic Darwinism'*** is that in order to explain the origins of biological complexity over such large time scales it is necessary to integrate and embed systems theory. Systemic Darwinism explores the extent to which three intertheoretical relations, namely, self-organising dynamics, cladistics, and function (evolutionary genetics) can be used to describe evolution. Laszlo (2009) puts it this way: "*Evolution: A cosmic process specified by a fundamental universal flow toward ever increasing complexity that manifests itself through particular events and sequences of events that are not limited to the domain of biological phenomenon but extend to include all aspects of change in open dynamic systems with a throughput of information and energy. In other words, evolution relates to the formation of stars from atoms, of Homo sapiens from the anthropoid apes, as much as to the formation of complex societies from rudimentary social systems*". A novel characteristic of living systems or systems established and organized by organisms (including human individuals and all social systems) is the capability of self-referential reproduction and multiplication, the autopoiesis (Varela *et al.* 1974).

The autopoietic nature of evolution suggests that the driving processes such as selection can be more complex than often understood and described. For instance, there is a debate on natural selection between two broad camps, those that argue the case for genic selection as championed by Dawkins (2006), and other biologists advocating hierarchical selection (Wade & Goodright 1998). Whilst the evidence for genic selection is convincing, it does not offer a satisfactory explanation for altruistic behaviour observed in certain social species. For instance, in certain primate societies, just as in human culture, traits that include fidelity, obedience and sharing are apparent but cannot be directly explained by "selfish gene" principles. Behaviour that would work against individual survivorship benefits higher levels of organisation—groups, families, societies. Consequently, clans, groups or tribes with a higher frequency of altruists are likely to survive, grow and develop further, as well cope more effectively with changing environmental conditions. Examples in nature where it could be argued that complex social behaviour has evolved in certain 'higher' taxa in response to living in unpredictable environments include Suricate meerkat, African lion, Hyena, African wild dog, Dog-faced baboon, and Gelada baboons, African elephant, and many Cetacean species. In each case the immediate concerns and needs of the individual are seemingly sacrificed for the 'greater whole' of the family/clan/community. However, especially in human social systems it has been seen that 'altruistic' behaviour can indeed be more or less directly rewarding and this is based on concepts of reciprocity (see below). Species that survive by social systems have evolved more complex behavioural patterns and mechanisms of communication, in some cases, rudimentary forms of language. In all cases these species have been highly successful in surviving extreme/high-stress environments, and utilising limited resources.

Another example of ecosystem complexity emerging through evolutionary pathways includes co-evolution. This phenomenon describes the tendency of different parts of a whole system to develop in a complementary way that makes them compatible. Nature reveals many forms of this relationship including commensal and symbiotic species. Also learning and absorptive capacity co-evolve with each other influencing the other (Lane *et al.* 2002). Increasing complexity and diversity in both symmetric and asymmetric interactions between organisms can contribute to the driving forces of evolution (Mitchell & Newman 2002). The evolutionary pathway of all of the diverse life forms follows a course set out by a 'blueprint'. This blueprint or template ensures the construction of structural and compositional diversity in nature—that in turn provides the means of overcoming chaos by acting to maintain continuity during change and transitions. However, it is a mistake to assume that evolution drives all life forms towards increasing complexity. This popular misconception is based on the preoccupation by science with the relatively small number of complex organisms that inhabit the "right-hand-tail" of the complexity distribution. The far greater mass of simpler organisms including the Prokaryotes and Protoctista that make up over 50% of the Earth's biomass are generally overlooked. More realistically, evolutionary forces drive systems towards increasing complexity only in a reduced number of subsets of nature.

ECOSYSTEM FUNCTION AND STABILITY

Historical perspectives of the diversity- stability hypothesis urge caution when searching for evidence of ecosystem stability and relationships between this and biodiversity (McCann 2000). Whilst several recent studies in this field have suggested that diversity can be expected to promote ecosystem stability it is unclear just what the driving forces are to this phenomenon. For instance, are there elements of more subtle trophic interactions between weakly interacting species in a system that are fundamental in regulating the more destabilizing consumer-resource interactions of dominant or keystone species (McCann 2000)? Furthermore, how is ecosystem stability defined? In general ecological terms it can be defined as both the optimum and permanent state of a population (Law & Morton 1996). This generality masks rather more intuitive considerations of dynamic stability and the ability of a system to defy change—resistance and resilience. A debate that focuses on dynamics and resilience in ecosystem stability is more likely to explore aspects of function and interactions between components as well as variability rather than obsess on species counts or the tendencies of certain charismatic taxa. This pathway of scientific exploration inevitably drifts outside the more traditional territory of equilibrium ecology and dynamics and into the realms of non-equilibrium paradigm. More recently, studies, particularly by Tilman and various collaborators working on plant community diversity and stability (Tilman & Downing 1994, Tilman *et al.* 1996), have converged on the finding that diversity tends to correlate positively with ecosystem stability. This relationship is not a direct linear one but rather has more to do with the collective effects of individual species responses to variable background processes—described as the ***averaging effect*** (Doak *et al.* 1998). These studies make clear that the findings cannot be used to infer that diversity has a direct causative effect on ecosystem stability. For instance, examination of this relationship at greater scales between ecosystems fails to support these findings (Sankaran & McNaughton 1999). Rather, a clearer relationship emerges between functional diversity and ecosystem function and stability (Hooper & Vitousek 1997). There is rather less research on functional diversity and ecosystem stability, particularly, at the level of trophic structure and dynamics. However, one examination of the grassland ecosystem of the Serengeti identified a positive correlation between a number of stability measures and diversity (McNaughton 1985). Beierkuhnlein & Jentsch (2008) interpreted their results of a series of experiments in line with the "*insurance hypothesis*" (Yachi & Loreaeu 1999) that species diversity contributes to the buffering of climate change impacts and increases resilience of ecosystems, due to species-specific responses. It has also been found that community responses are not exclusively controlled by intrinsic responses, as stress-induced invasions may modify ecosystem stresses: e.g., in grasslands and heath systems, heavy rainfall events increased invasibility, and drought reduced it (Kreyling *et al*. 2008).

Both theory and empirical evidence point towards an understanding that the persistence of complex systems depends on the variability (fluxes) of populations and the changes in dynamics between species. These differential species responses influence the functionality of the whole system by weakening the destructive potential of competitive exclusion and thus stabilising a system and increasing its resilience to change (McCann 2000). In conclusion, the role of biodiversity in maintaining dynamic equilibrium in complex ecosystems is fundamental and cannot be undervalued.

ENERGY FLOW, CHAOS AND SELF-ORDERING IN NATURAL SYSTEMS

Solar energy creates existence, and nature is the only system that has the capacity to build and concentrate material substances from an external source, the sun (Wall 2005). It is this capability of nature to build structure and order within a system that enables it to conserve and store the energy for use at a later time. Stored energy that can be accessed from within the system is referred to as **exergy (usable energy)**. The relationship between exergy and biological structures defines the complexity of systems, and more complex systems demonstrate greater efficiency at degrading incoming energy (Baldwin *et al*. 2004b). Exergy creates structures, and the more structures to evolve in a system, the greater the efficiency in capturing and banking it for future use—"***exergy capital***" (Wall 2005). However, this is not the complete story. Inevitably, exergy destruction occurs as a result of unpredictable disturbance events or from exploitation by elements within a system. New sub-systems emerge within the super-system—'matter-simplifying' species that interact with primary producers by breaking down accumulative matter and releasing it back into the system thus contributing to the feedback processes (Baldwin 2004). In Holling's adaptive cycle this is demonstrated by the shift in state from a position of conservation to that of change—the release or transference of energy. It is the destruction of exergy that creates the necessary change in systems that allows for evolution and adaptation (Wall 2005). The description of the universe or an ecosystem in complete equilibrium implies that there is no exergy. Conversely, the ultimate conservation state of exergy in a system would describe a situation in which everything could be returned to an original state and changes could be reversed. In this scenario time would have no meaning or direction (Wall 2005). However, this is not how natural systems work, rather, change is integral to system dynamics; exergy is destroyed; time has defined trajectories; and the whole process is irreversible.

Self-ordering in natural systems is not enough to promote and sustain biodiversity. Without renewing processes and periodic disruptions natural competition and the constraints of order restrict opportunities for the re-assemblage of new forms of diversity. In other words, biodiversity functions at the 'fuzzy' boundary between chaos and order—the "ChaOrd" zone (Huston 1994). The frequency, scale and force of disruption are a determining factor in creating appropriate conditions for biodiversity. Too much disturbance degrades the ecosystem and ultimately drives it towards a regime shift. Biodiversity provides a system with its ecological integrity and helps maintain it at its optimum operating point or equilibrium. The extent to which a system is moved from this point is determined by the force of environmental change. Natural disturbance and **stress** affect ecosystems as either on-going events—intermediate disturbance, or as novelties—catastrophic impacts. Small scale shifts that result in the emergence of meta-states provide an ecosystem with the necessary resilience and adaptation to changing conditions. For instance, changing climatic conditions induce geographical range shifting of biological systems such as populations or species. The reduction of resource availability can also lead to a decrease of sub-system density (e.g., individuals per area). Under extreme conditions the shift of an ecosystem to new operating points can induce dramatic changes to its complexity, functions and characteristics. Consequently, it experiences **degradation or even collapse**. Ecological examples would be forest ecosystems that lose structurally important species which are replaced by others, better adapted to new conditions (e.g., increased aridity or higher grazing intensity), and that degrade to grasslands. The corresponding *adaptive degradation* is related to important changes of emergent properties such as ecosystem functions (e.g., living biomass production, water filtration, soil formation). In extreme cases of degradation, especially when it occurred very abruptly and fast, the internal organisation of systems breaks down, and, ultimately, ecological integrity is lost in a **collapse** (e.g., extinction of a population or species; loss of ecosystems due to erosion following structural degradation).

The ability of a system to recover from disturbance and return to an optimum operating point describes its **resilience**. Biodiversity is fundamental to ecosystem resilience, and the more species there are together with a strong contingency of specialists the greater the functionality and integrity of the system. Functional and evolving systems that are able to return or shift to operating points without losing fundamental and typical emergent properties **develop sustainably** (Ibisch 2010). However, as change is inevitable, **sustainability** does not imply a maintaining of the status quo, but more appropriately, may describe a system undergoing a building phase towards complexity through the increasing evolution of sub-systems (attractor basins) or indeed shifts in meta-state of existing attractor basins. In both cases the super-system develops resilience and adaptation to change. In this description sustainability does not imply active human intervention but rather a natural process manifest in emergent properties of functional systems. **Sustainability**, when applied to 'free-willed' systems, defines the single or multiple states of dynamic equilibrium—the ultimate 'gravitation' of systems towards attractor basins. Any external gradient that causes fundamental shifts in a system, enough to create a hysterisis effect, will inevitably bring about destabilization and loss of sustainability. In response to this shift a new regime will emerge with its own attractor basins and parameters of sustainability or the system will decline to a point of no return (Lyytimäki & Hildén 2007).

As stated in the previous paragraphs, the condition and behaviour of nature is defined by its relationship with energy. The persistence of life on earth is a measure of the ability of ecosystems to avoid equilibrium by moving themselves away from the point of entropy. To better understand this relationship between systems and energy there is a need for new concepts and metaphors to complement the theories of adaptive cycle and complex systems theory. There are clear advantages to examining systems through the study of energetics– energy is easily measured and can provide empirical evidence for the performance, capacity, and limitations of systems. By the turn of the 20th century scientists were familiar with some of the basic principles of **thermodynamic**s. However, more recently, these principles have been developed and used to describe the behaviour and performance of ecological and social systems.

B. 2.1.b THERMODYNAMICS AS A PRIMARY DRIVER OF SYSTEMS

THERMODYNAMIC EFFICIENCY AS AN OVERARCHING PRINCIPLE IN NATURE

At the end of the 19th century, Boltzmann (1886) attempted to develop a better understanding of nature by describing the apparent order observed in nature using the second law of thermodynamics. His explanation of ordered nature was of a system in transient state that would inevitably decay towards death and disorder. However, confounded by the obvious contradictions between heat death of the universe and the evolution of complex ecosystems on earth, Boltzmann recognised the need for an alternative perspective to describe the relationship between living systems and energy. Over half a century later this same paradox preoccupied another scientist, Schrödinger (1944), who described two fundamental processes that were responsible for the coherent patterns and dynamics of nature. The more obvious process was "order from order" that conveyed the consistency of inherited traits and form under the control of DNA, that is then passed on from generation to generation. The second more complicated process was "order from disorder" that explained the ability of nature to apparently defy the second law of thermodynamics by moving a system away from a state of entropy through the continuous biological evolution of self-organising constructs (compare Nicolis & Prigogine 1977).

At the organismic level, autotrophic beings such as plants are assembled from a 'disordered soup' of carbon molecules. This creation of order from disorder can happen only because of the use of energy that is taken from other systems in which entropy inevitably has to increase. The green plants use solar energy, and the corresponding increase of entropy would happen in the sun anyway. The situation is different in the case of the derived heterotrophic organisms. On the one hand, the decomposers are important in terms of thermodynamic and material efficiency because they recycle nutrients required for the establishment of new and more systems; they live from energy provided by other disintegrating systems. On the other hand, the consumers can create order only at the cost of increased entropy in other living systems on Earth. Order of autotrophic or other heterotrophic organisms is naturally disrupted by the generation and ultimate ordering of the next trophic structure—the consumers. At each stage of ordering energy is both utilised and also lost to heat. This suggests woeful inefficiencies in the hierarchical structuring of nature, particularly, in the simplified analysis of food chains. However, natural systems are rarely constructed along such simplistic lines of organisation. For instance, competition amongst plants is strongly influenced by the activities of herbivores—one of the principle drivers of change and evolution in the plant world. This relationship between producer and consumer encourages increasing diversity in plant form and function, for instance efficiency gains in the dissipation of energy. In this context, it is important to acknowledge that the biomass that can be established by consumers is thermodynamically limited—and it must be always at the order of magnitude smaller than the biomass of autotrophic organisms (compare Odum 1971). At the same time, the diversity of heterotrophic lifeforms can be much larger than the diversity of autotrophic ones, because they have many more options for gaining energy by exploiting existing autotrophic or other heterotrophic systems.

Another implication that becomes obvious, is that whenever heterotrophic organisms appropriate and turnover a significant amount of energy provided by and dissipated in autotrophic organisms, this will lead to decreasing **thermodynamic efficiency** of the ecosystem—which is a measure of its sustainability in terms of auto-regulating the system and maintaining it in a certain attractor basin. Incoming energy is degraded at all scales in an ecosystem and in landscapes dissipating structures manifest as spatially heterogeneous patches (vegetation formations), biomass accumulation, and trophic complexity. As more species assemble in a landscape the interconnections between the living and non-living components become increasingly more complex. The measure of this emerging complexity and the corresponding increase in functionality would indicate the amount of incoming energy being captured, dissipated and degraded by the system. The efficiency of this process would also show in the complexity of trophic connections, specialization of the resource niche, and the extent of recycling and biomass accumulation (Kay & Schneider 1992). Evolution is the driving force behind system organisation and as such could be defined as a process that, under the physical laws of nature, produces systems, which are able to self-organize, multiply, reproduce themselves and diversify at the cost of increasing entropy in other systems. This leads to increasing opportunities of interactions between systems and corresponding complexification of systems of ever higher order (Ibisch 2010). The ability of systems to self-organise enables them to evolve and function some distance away from thermodynamic equilibrium. In other words, they exist in a non-equilibrium, quasi stable state by avoiding entropy (Kay 1992). Biodiversity is the 'solution' to the thermodynamic problem of maximising the degradation of solar energy. However, as mentioned before, a system's ability to exchange energy with the outside environment comes at a cost of increasing the entropy of the larger environment. The signatures of a thermodynamically efficient system include the following:

- the emergence of stable dissipative structures (complex cycles and diverse, representative species)
- growth of the physical-biological structure (biomass)
- growth in complexity of the network between the components
- and growth of 'information' (increase in the proportion of more complex organisms with K-strategy to those with r-strategy) (Jørgensen 2006).

An increase in the input of 'exergy' and material can push a system beyond a boundary from thermodynamic equilibrium. The system responds by using the exergy to construct and maintain its structure. As a result of the dissipation of this exergy, the system retains its position away from thermodynamic equilibrium. Over time, the continued influx of exergy prompts a response of more emergent structures to degrade the exergy. This behaviour promotes increased complexity and corresponding efficiency in acquiring resources and constructing more dissipating structures. Plants utilise the incoming solar energy to produce complex compounds and stored energy. The stored potential energy of the producers is then exploited by consumers and ultimately chains of these trophic groups will build up in complexity within a system. The result to the incoming energy is that it is degraded as it passes through the various biological processes of respiration and metabolism. These "chains of events" are referred to as **'energy degrading chains'** (Kay & Schneider 1992). However, there is a finite point to this process and eventually the system will reach a critical state beyond which self-organisation breaks down and chaos ensues. This rather suggests that ecosystems operate on 'boom—bust' cycles of collapse and re-invention and yet this is not what is witnessed in most cases. What prevents a system from flipping between these two extreme ends of dynamics? Certainly, the interaction both within and between species across all trophic levels plays a central part to the maintaining of ecosystem equilibrium and resilience. The sheer mass of numbers and diversity of forms presents a picture of chaos with little sense made of the relationship between any specific event and interaction. For instance, in a grassland ecosystem the pursuit of a small rodent by a bird of prey has no rationale connection to the pollination of a flower by a bee or to the fungal attack of a soil nematode. Yet, the intricate and apparently chaotic events that play out across space and time generate the self-ordering feedback mechanisms that regulate the energy flux in an ecosystem.

Complementary to the process of building order and structure by means of energy degrading chains is another essential function that involves the mechanical and physiological break down of compounds—**'matter simplifying'** (Kay & Schneider 1992). This process makes available the essential compounds and elements needed in energy degrading chains, and both functions may occur at the biological level within trophic groups or between trophic levels. Thermodynamically efficient, dissipative systems can respond to environmental change in different ways depending on the level of disruption.

THE PARADOX OF OPEN SYSTEMS AND ENERGY CONSERVATION IN NATURAL SYSTEMS

In previous sections of this paper a description of systems characterised them as self-organising constructs operating under feedback mechanisms and open to the exchange of energy and material. However, ecosystems are spatially and temporally constrained. For instance, the physical environment, microclimate and availability of free or mobile resources restrict the extent, size and shape of ecosystems. Equally, temporal influences including large-scale evolutionary changes and much shorter time lines representing responses to periodic disturbance also help define ecosystems. These spatio-temporal references create the distinctive patterns and mosaics that give a landscape its character. A well-defined ecosystem has strong interactions among its components that are not expressed across its boundaries (Jørgensen 2007). This is partly due to the coinciding of discontinuities in abiotic conditions, and also in the distribution of species. The diminishing of self-recognising tendencies at boundaries puts limits on the exchange of matter and energy. Vegetation dynamics play a fundamental role in defining the parameters of terrestrial ecosystems; they are the means of harnessing the raw energy of the sun and converting it into bio-chemical factories. The efficiency, or more correctly, inefficiency of plants as energy capturers sets the thermodynamic limits of an ecosystem. At its most efficient, nature can just about harness between 2%–3% in the form of plant biomass production (Vitousek *et al.* 1986). In equatorial regions plants operate at their most efficient allowing ecosystems to optimise their trophic structures, diversity of species and accumulation of biomass. However, even the very largest equatorial ecosystems are bounded by spatio-temporal constraints and energy conversion inefficiencies that create a landscape of semi-closed multi-systems. This limitation to system growth falls below the thermodynamic expectations of a system and are more likely to be a result of ecological constraints to trophic transfer of energy. That is not to suggest that a system very close to physical limits cannot still continue to grow. Rather, a system is likely to shift towards improvements in matter recycling and increases in information (Jørgensen *et al*. 2007). This process of internalising and re-cycling energy and matter transference (self-ordering) reduces the exchange of materials across borders between systems and this has advantages of retarding the lowering of energy flux and increasing energy-efficiency. "*To this end, functional units with minimal openness may be readily recognised at every fractal level: atoms with electrons distributed in orbitals about the nucleus; molecules with several atomic nuclei and electrons in molecular orbitals; molecular aggregates from water (H_2O, H+ and OH-), salts and macromolecules, with clusters stabilised by electrical interaction; cells with their functional organelles; organisms with their different cell aggregates and organs*" (Ripl & Wolter 2002).

In ecosystems the dissipative ecological unit (DEU) is the smallest functional unit of a functional ecosystem (e.g., Ripl 2003). "*For single-celled organisms, the efficiency principle already applies: the more effectively the cell can turn over the material running through structured cyclic processes and the fewer losses it makes, then the more stable and thus more survivable it becomes. Thus, the intake of food needed for operating processes is minimised. In multicelled organisms, this efficiency criterion is supplemented by the synergetic division of labour between cells and cell tissue—and by the organism's internal transport systems. (…) In addition, multicellular organisms minimise a part of their irreversible losses by cycling material internally*" (Ripl & Wolter 2002).

At larger scale breaks, for instance, intra-specific and inter-specific levels of organisation, close coupling between two organisms can improve efficiencies in capturing energy and material, and there are numerous examples of this relationship. For example, symbiotic nitrogen fixation between plants and bacteria, mycorrhyzal associations between fungi and plants, the mutual existence between algae and fungi in lichens, and between algae and certain species of Coelentorates or Crustacea; and so it continues even in higher life forms. More obvious interactions among organisms cover such familiar topics as competition, predation or herbivory. Patterns of organisation that promote energy efficiency occur at different fractal hierarchies within a system by following the same principles and adopting the Dissipative Ecological Unit (DEU) (Ripl & Wolter 2002). At these higher levels of organisation energy and matter-transferring pathways are a function of the complex network between the components. Furthermore, as a system grows and adapts, the corresponding networks increase and change. Ultimately, a system becomes too complex to be able to apply laws of thermodynamics and a more holistic and unifying theory is called for—Ecosystem Theory (Jørgensen & Fath 2004).

In recent years a number of scientists have worked towards developing an ecosystem theory, in particular, Jørgensen and Fath (2004) have proposed a conceptual model consisting of eight basic laws. This has since been modified to nine laws that unite principles of thermodynamics and systems theory (Jørgensen 2007). The nine laws are stated as follows:

1. *All ecosystems are open systems embedded in an environment from which they receive energy-matter input and discharge energy-matter output*
2. *Systems have many levels of organisation and operate hierarchically.*
3. *Thermodynamically, carbon-based life has a viability domain determined between about 250-350K.*
4. *Mass, including biomass, and energy are conserved.*
5. *The carbon-based life on earth, has a characteristic basic biochemistry which all organisms share.*
6. *No ecological entity exists in isolation but is converted to others.*
7. *All ecosystem processes are irreversible.*
8. *Biological processes use captured energy (input) to move further from thermodynamic equilibrium and maintain a state of low-entropy and high exergy relative to its surroundings and to thermodynamic equilibrium.*
9. *After the initial capture of energy across a boundary, ecosystem growth and development is possible by (1) an increase of physical structure (biomass); (2) an increase of the network, more cycling or; (3) an increase of information embodied in the system.* (Jørgensen 2007)

The relationship between complex system structure and thermodynamics is described in the growth and development of an ecosystem. Young ecosystems capture much of the incoming energy through the build up of biomass (Growth form I). This is a period of high productivity, the 'autotrophic' phase of an ecosystem, when net primary production is greater than 1 (Brewer 1994). However, as systems mature and experience physical and ecological constraints they move towards greater complexity, the heterotrophic phase—a process of increasing networks and information (growth forms II & III). By this stage of development energy captured by the ecosystem has levelled off and net primary production would come close to 0. Apart from an increase in trophic structure there are also changes in species strategies, a shift in emphasis from generalists and r-strategists to specialists and k-strategists (Jørgensen 2006). This period in the ecological history of an ecosystem represents the period of sustainability.

Ecosystem theory draws together much of the thinking and research on systems theory and ecosystem thermodynamics. It offers appropriate narratives and metaphors for understanding the relationship between natural and anthropogenic systems. It also sets out clear parameters and measurable boundaries to systems in terms of productivity, carrying capacity, limits of change, resilience, as well as factor in the unpredictable nature and uncertainty of system behaviour. In other words, ecosystem theory provides a robust baseline on which to build an informed framework for sustainable development.

NON-EQUILIBRIUM THERMODYNAMICS AND SUSTAINABILITY

There is a long-standing dispute about the application of thermodynamics to sustainability science. Especially the work of Georgescu-Roegen (e.g., 1971) has stimulated a debate about the relevance of entropy. A common misunderstanding in this debate is that entropy is often represented as an anthropogenic problem on Earth, rather than an inevitable consequence of thermodynamics as defined in the second law (e.g., compare Schwartzman 2008). The increase in entropy in the wider environment is the necessary requirement for the emergence and maintenance of self-organized systems, it is nature's evolutionary pathway to survival. The debt of self-organizing systems to chaos is the environmental increase in entropy. Consequently, the critics of the so-called neo-Malthusians (who describe the existence of limits to human growth), claim that a "*sustainable societal self-organization on the planet Earth is only limited by the low-entropy solar flux, a limit with no practical consequences far into the future, with the entropic debt paid as the heat flux to space, the ultimate heat sink*" (Schwartzman 2008). These technology-believing critics overlook the enormous complexity of natural ecosystems, their functions and services the anthroposystem depends on. Of course, theoretically, it would be possible to design a solarized and almost dematerialized world where almost any ecosystem service is replaced by solar power (or atomic fusion power) fuelled technology, including artificial photosynthesis for food production. This, however, seems to be mere science-fiction ignoring most of the known emergent properties of natural and social systems. In natural systems sustainability can be defined as the sum of the relationships between energy and biodiversity, more specifically, the interconnection of three fundamental processes of energy utilisation. These are: (1) energy input from the sun that creates existence; (2) the dissipation and storage of exergy that creates structure; and (3) the destruction of exergy that creates change (Wall 2005). In complex, thermodynamically efficient systems the energy and materials are recycled and the net primary production approaches 0 value. The development of structures and biomass in a system constitutes the "exergy capital", the necessary surplus 'banking' of material that provides insurance against entropic collapse.

Exergy capital takes many forms in our Earth's system; the most obvious are coal, peat deposits, oil, natural gas, plant and algal growth and detritus, as well as other trophic life-forms. These structures and forms transcend across scales from the very large biomes to smaller units of vegetation—logs and leaf litter strewn across the forest floor. Rather than wasteful, natural systems are efficient in harnessing exergy to create new structures, the stuff of biodiversity. A small proportion of material is stored away in the lithosphere, but this 'banked' matter is not waste, rather, it has played a key role in shaping the planet over the last few billions of years. By removing a proportion of biomass from the biosphere and storing it in the lithosphere, new opportunities arose for species to evolve and expand into the 'space' made available. Global catastrophic events in the past such as extreme volcanic activity have unleashed some of this stored biomass in the form of debris and carbon dioxide, causing wide scale destruction across large tracts of the planet.

Our relationship with energy and the planet's exergy capital is unique. The advancement of technology has made it possible to tap into exergy capital reserves, including coal, oil and natural gas that are out of the reach of other species. There are two aspects to this exploitation: resource depletion and environmental destruction (Wall 2005). Materials extracted from the lithosphere, both organic and mineral, are processed into derivatives that are either more concentrated, refined, distilled or volatile versions of the original parent substance. Damage to the environment occurs at all stages of this conversion process. In most cases there is no recycling of material substances. Instead, processes that are more typical of positive feedback mechanisms are applied to extract substances from the lithosphere, utilize the refined products and re-deposit the residue as toxic waste in all other four geo-spheres (Wall 2005). The accumulation of toxic waste and by-products may take nature millions of years to repair. Furthermore, as material in the lithosphere is depleted, the quality of remaining deposits decreases and so more exergy is required to extract what is left. An assessment of the extent of human exploitation of natural and exergy capital claims that between a third and a half of the Earth's land surface has been transformed by human development, and one third of the planet's terrestrial ecosystem production (Vitousek *et al.* 1997). Growth of the anthroposystem and improved quality of life has placed excessive dependence on specific energy forms, specifically electricity that is generated by non-sustainable and non-renewable energy sources (Dincer & Rosen 2005). The total energy consumed by civilisation is calculated at 13 Terawatt and in the next fifty years it is expected to reach a level of 30 Terawatt (Daily *et al.* 1994). If thermodynamic laws and principles of sustainability are to be applied, then optimum levels of energy utilization are estimated at 2 to 4 Terawatt, which would extrapolate to a global population of 1.5 to 2 billion people. What is more, 75% of the world's energy is utilized by the industrialised economies that make up only 25% of the world population.

The laws of thermodynamics make it quite clear that on matters of energy there is an inevitable single direction to go with no way back. As work is done the quality of energy is degraded and as a result systems move closer towards entropy. This inherent production of entropy cannot be reversed (Schmitz 2008). Since the dawn of civilization, but more significantly in the last 200 years, the rapid development of socio-economic systems, including the dramatic transformation of global ecosystems to cultural landscapes, has accelerated the degradation of the planet's exergy capital. The global ecosystem is simply getting hotter, it is losing its resilience and capabilities to dissipate energy, there is less biomass storage in the system, and dissipative structures are undergoing simplification. During the very brief period of civilization the advances of technology have created a false sense of limitless resources and opportunities. Society has been tricked into thinking that both science and technology are able to skip round problems of energy and material shortages, and that there is ultimately an answer to the dilemma of energy-exergy-entropy. It is the belief that 'laws' can be made and broken that lulls civilization into a false sense of security and drives it ever forwards beyond the limits of nature's boundaries.

So far, we have set out some of the philosophy and science underpinning current understanding of complex systems and thermodynamics. These sections provide the necessary theory to the environmental elements of sustainable development. However, to complete the foundations for sustainable development it is necessary to provide an account of human evolution and development, and the intimate relationship between civilization and the natural world (see next chapter, Ibisch & Hobson, B2.2., in this document).

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