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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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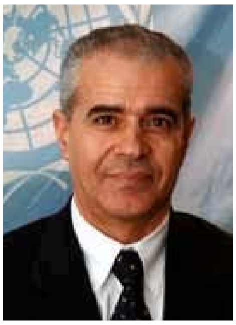

At its second meeting, held in Jakarta, November 1995, the Conference of the Parties of the Convention on Biological Diversity adopted the ecosystem approach as the primary framework for action under the Convention. The Ecosystem Approach recognizes that humans, with their cultural diversity, are an 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.2.3 STRATEGIC SUSTAINABLE DEVELOPMENT: A SYNTHESIS TOWARDS THERMODYNAMICALLY EFFICIENT SYSTEMS AND POST-NORMAL COMPLEX SYSTEMS MANAGEMENT

Peter Hobson & Pierre L. Ibisch

ABSTRACT

Fundamental issues to do with unsustainable human development and energy management that lead to converging crises such as biodiversity loss or climate change require urgent attention if global society is to progress in a sustained way in the long-term. Measures of thermodynamic efficiency go beyond the obvious relationship between society and energy resources, to also include the way humans utilize the physical and biological landscape. A number of metrics are proposed in the assessment of environmental sustainability including the use of exergy. However, attempts to measure the sustainable use of the physical landscape and living biota are more problematic because of the complexity of nature. Nevertheless, there is emerging scientific evidence in support of the idea that there is a strong relationship between vegetation pattern and thermodynamic factors. Furthermore, an examination of land cover type and microclimatic patterns suggest that mature and complex ecosystems have the highest levels of exergy and are better able to dissipate solar radiation. This suggests that more complex, thermodynamically efficient systems are more resilient to environmental change.

Both landscape ecology and industrial ecology provide a range of useful proxy measures of thermodynamic efficiency for ecosystems. By reducing often confounding patterns and behaviour of complex systems to practical measurements of energy use it is possible to construct a robust framework for sustainable development. Human social systems mimic some of the non-equilibrium thermodynamic patterns found in nature. Materials and energy are processed and re-cycled through a nested hierarchy of semi-closed systems. However, there are fundamental differences between the two domains that relate to scale, structure, dynamics and feedback mechanisms, and it is this difference that may contribute significantly to the ultimate breakdown in natural systems, biodiversity loss and anthropogenic climate change. Most of Earth's biodiversity continues to exist outside the boundaries of protected areas and within the used landscape. This situation is unlikely to change in the future, although land use practices under the current scenario of "business as usual" will continue to drive down biodiversity and ecosystem services. To tackle problems of this magnitude and complexity a framework for sustainable development is needed that operates to optimum indicators for ideal-seeking systems based on non-equilibrium thermodynamics and complex systems theory.

An effective assessment of the sustainability of a system would include an ecosystem mapping exercise and the use of a predictor set of complementary proxy indicators; these could include, for instance, the quantity of energy input and utilization; exergy capacity (stored, usable energy in the system, carbon storage); and measures of various positive feedback processes (quantity of non-recyclable energy and material—waste material and heat loss/capacitance), or connectivity/connectedness). Adequate biodiversity indicators would comprise of biomass production/carbon storage; diversity of native primary producers (species richness); diversity of plant growth forms (functional groups, strategic types); and a "trophic tree index"—the number of functional groups of fauna and flora.

Science and technology should re-focus efforts towards eco-centric innovation, methods of working towards ideal-seeking systems using principles of thermodynamics. Fundamental to this change is the reform of neo-classical models of economy that embrace principles of ecological economics. The validation of the ecological economics model is underscored by the primary objective, which is to ground economic thinking and practice in the laws of thermodynamics. Success, goals and outcomes should not be exclusively measured in monetary worth, but also by using relative valuation and environmental accounting.

B.2.3.a THERMODYNAMICS-BASED SUSTAINABILITY

The relationship between energy and biodiversity sets the context for the evolution of life-forms and ecosystems and provides the means for advancing human civilization and generating wealth (Dincer & Rosen 2005). Energy use and transference within and between systems is governed by the laws of thermodynamics, which provide clear and unambiguous pathways to a more sustainable management of resources (Dincer & Rosen 2005). Currently, society is operating unsustainably and a combination of human-resource-related behaviour has contributed to a number of problems including biodiversity loss, global resource depletion, and energy-related environmental impacts. Fundamental issues to do with human development and energy management require urgent attention if global society is to progress in a sustained way in the long-term. Measures of thermodynamic efficiency go beyond the obvious relationship between society and energy resources, to also include the way humans utilize the physical and biological landscape.

Discussions on thermodynamics-based sustainability emphasize the importance of minimising the influence of subjectivity in formulating appropriate strategies and indicators in the process. A number of metrics are proposed in the assessment of environmental sustainability including the use of exergy (Dewulf & van Langenhove 2005). Exergy analysis quantifies energy use including losses and waste at various stages of its progress through a system (Dincer & Rosen 2005). Consequently, it is possible to calculate the amount of non-renewable exergy necessary for the life-cycle of a certain product or process (Sewalt *et al.* 2001; Hammond 2007). The loss of exergy from non-renewable sources is considered to be toxic to the environment. By contrast, renewable exergy sources do not produce any harmful effect since they can be recovered (Sewalt *et al.* 2001). It is easier to appreciate the quantitative benefits of thermodynamics in industrial systems that operate to mechanistic and measurable energy flows, and there has been a good deal of research on the use of exergy and other sustainable metrics to measure efficiencies in these systems (see Connelly & Koshland 2001, Dewulf & van Langenhove 2005). Furthermore, the potential use of exergy analysis in assessing the impact on the environment of waste material is significant (Dincer 2000).

However, attempts to measure the sustainable use of the physical landscape and living biota are more problematic because of the complexity of nature. Certain principles of energy and material transference used in industry can be applied to natural systems. Aspects of energy exchange, and conversion and the effects of mass (biomass in the case of biological systems) influence life-cycles of species and material as well as biological processes (Dewulf & van Langenhove 2005). For instance, by measuring the energy and material input into agro-ecosystems together with product output, it is possible to estimate the production of entropy (Steinborn & Svirezhev 2000). In a similar way, the entropy of a landscape can be assessed by measuring the differences between the values of biogeoceonosis sensitivity (sensitivity of both species and environmental attributes) and technogeochemical stresses (pollution, contamination and physical alteration) that result from human activity (Jankauskaite & Veteikis 2005). The ability of a landscape to process toxic waste and 'self-clean' is a measure of the extent of biomass deposition and circulation, which, in turn, is a proxy indicator of complexity, resistance and resilience to anthropogenic influence (Jankauskaite & Veteikis 2005). In other studies that have examined the organizational order of vegetation, a relationship between vegetation pattern and thermodynamic principles has been demonstrated (Zhang & Wu 2002). Taking it further, an examination of land cover type and microclimatic patterns suggest that mature and complex ecosystems have the highest levels of exergy and are better able to dissipate solar radiation (Wagendorp 2003).

More recent developments in landscape ecology have moved the science closer towards a holistic problem-solving discipline that explores connectedness and ordered complexity rather than conventional lines of enquiry based on reductionist and mechanistic approaches (Naveh 2000). Central to this concept is the recognition of the human ecosystem as a holarchic subset to the global ecosystem, and its reliance on the combined input of solar and alternative-based energy. This approach attempts to unify principles of ecology and thermodynamics into a coherent ecosystem thesis that offers appropriate metaphors and measures for sustainable development (Naveh 2000).

Both landscape ecology and industrial ecology provide a range of useful proxy measures of thermodynamic efficiency for ecosystems. By reducing often confounding patterns and behaviour of complex systems to practical measurements of energy use, it is possible to construct a robust framework for sustainable development. Thermodynamic modeling and measurements of ecosystem performance would provide the necessary guidance for policy on social and economic development towards a whole-systems approach. Furthermore, it would avoid potential conflicts between various global frameworks, for instance, the Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity (CBD). At the moment, there has been little effort to align the objectives for carbon management and ecological sustainability (e.g., Muys *et al.* 2003).

The next stage to the process of developing a unifying framework for sustainability is to link structural and functional attributes of biodiversity to thermodynamic measures of anthropogenic disturbance. So far, scientists have provided a theoretical framework for ecosystem thermodynamics (Holling 1986; Jørgensen 1992; Schneider & Kay 1994; Kay *et al.* 1999; Kay 2000). Attempts to attach measurable indicators of ecosystem exergy efficiency to this theory have brought us closer to defining the capacity and limits of global ecosystems (Jørgensen 2006). However, there are still gaps in the model that fail to take full account of temporal and spatial scales of biodiversity. Historical and environmental legacies of biodiversity configured across landscapes provide connectedness, and contribute to emergent properties that are difficult to categorise using principles of thermodynamics. What is more, land use has and continues to change these natural patterns, often leading to biodiversity degradation and ecosystem dysfunction. There is a need to devise a conceptual framework and practical set of measures for these aspects of biodiversity. The ecosystems theory makes a significant contribution towards capturing biodiversity value (Jørgensen 2007). A unifying concept for sustainability would combine principles of ecosystem theory and structural biodiversity.

Achieving sustainable development requires a holistic systems approach as suggested by Robèrt *et al.* (2002). They define five hierarchical and inter-dependent levels for a systems approach for *strategic sustainable development* (SSD). The following suggested principles broadly embrace the philosophy underpinning SSD. Macro socio-economic policy should be built on an ecological platform in which opportunities and constraints are identified in the context of ecosystem carrying capacity, resilience and thermodynamics. In this model the socio-economic infrastructure is an integral, scaled subset within the space-time dimensions of the natural system. This sets clearly defined limits on human population growth and utilization of energy and natural resources. It also requires a complete re-adjustment of the shaping and function of a cultural landscape. Patterns of use and processes would change profoundly to minimise loss of ecosystem complexity, structure and biodiversity in order to fit as best as possible within natural forms of thermodynamic efficiency. Such a strategy amounts to 'mimic-management', synchronicity with natural feed-back systems, disturbance regimes, and space-time heterogeneity. Conceptual coherence, inter-connectedness and dynamic time dimensions are factored into the framework. Management of human systems and cultural landscape is required to be adaptive and pro-active, flexible enough to factor in environmental uncertainty. This requires a shift away from human activities and systems that promote resistance and steady state to those that create resilience. In the landscape, practices that promote the retention of environmental legacies, specifically key functional ecosystems, including forests and wetlands, should become benchmarks for future development.

Achieving sustainable solutions is also about engaging with social values and individual behaviour. Existing 'life-value' references such as biodiversity, environmental mitigation, nature-worth, life-quality indicators and well-being that are currently traded as monetary-driven commodities would be re-valued under an ecosystem services credits system. As such, they would be traded and banked by organisations and governments operating to novel bio-economic structures and regulations.

Science and technology would re-focus efforts towards ecocentric innovation, methods of working towards ideal-seeking systems' using principles of thermodynamics. Essentially, it calls for a Radical Ecosystem Approach that combines principles of ecosystem theory and non-equilibrium thermodynamics (Ibisch *et al.*, A.2., in this document).

B.2.3.b A POST-NORMAL SCIENCE PERSPECTIVE ON BIODIVERSITY AND SUSTAINABILITY

Biodiversity has been shaped by chaotic events that have generated order across scales of space and time. In a "neutral environment" devoid of life, the energy imported from the sun or generated from chemical and thermal reactions would soon reach a state of entropy according to the laws of thermodynamics, with no means of recycling energy and building exergy capacity. Living systems, on the other hand, have evolved a unique way of capturing the sun's energy and dissipating it through self-organizing and complexifying structures. Furthermore, feedback processes operating in semi-closed systems have improved functional efficiencies by recycling energy and material thus delaying the inevitable end-point of entropy, a very non-equilibrium thermodynamic characteristic.

Human social systems mimic some of the non-equilibrium thermodynamic traits found in nature. Materials and energy are processed and re-cycled through a nested hierarchy of semi-closed systems. However, there are fundamental differences between the two domains that relate to scale, structure, dynamics and feedback mechanisms, and this discourse is the cause of systems breakdown, biodiversity loss and anthropogenic climate change. Detailed scientific investigation has identified many of the causes and effects of these problems, and the findings of these studies have been used to inform policy on sustainable development. What then is the issue, and why are so many of the problems re-occurring and exhibiting accelerated tendencies towards collapse? There are growing concerns in various sectors of society that science is failing to provide adequate responses to the challenges facing humanity, and ultimately, is facing a crisis of confidence. Science has amassed a wealth of knowledge of the components, elements and attributes of the natural environment but little understanding of the interconnections and synergistic tendencies that binds them into a functioning complex system.

In some cases it is possible to find a plausible scientific reason for these failings whilst other problems remain beyond the powers of reasoning or action. For instance, density-dependent factors of population carrying capacity are readily explained through the relationship between population numbers and food availability using an interpretation of the Lotka-Voltera model. That is not to suggest that relatively linear models for cause and effect problems necessarily respond readily to equally simple solutions. For instance, attempts so far to address problems of population growth and over-exploitation of resources have failed because the human relationship with exergy capital is much more complex than this. Technology has made possible the extraction, processing and transportation of energy and material from more than one source, and this in turn, has de-coupled society from some of the constraining factors that bind the rest of nature. History provides evidence for this unique phenomenon of nature-culture de-coupling as far back as early hunter-gatherer societies. The discovery of fire provided a powerful tool for the dramatic transformation and shaping of the landscape. Later, the birth of agriculture catapulted civilization from hunter-gather to harvester of crops and animals, followed by the industrial revolution that accelerated the pace of human development and expansion into virgin landscape, and so it goes on. The consequences of these phenomena were a rapidly increasing population that was able to form semi-permanent settlements in concentrations higher than the natural carrying capacity of the original ecosystem. Each historical phase in human development has marked a fundamental change in our relationship with nature including the extent to which we are able to exploit exergy capital (compare Ibisch & Hobson, B.2.2., in this document). As a consequence, humanity has created multiple meta-systems within the biosphere, thus adding to the complexification of the global ecosystem. These developments have brought with them novel emergent, indeterministic properties that have added to the existing mountain of unknowns in the science world.

Here is the paradox, despite the mimicry and interconnections between cultural and natural systems, the popular world view (scientific and philosophical) is of a technocentric society that is able to grow and function unfettered by 'laws of nature.' This, in turn, has shaped modern society's perspective on the human-nature relationship. Societal segregation from the living world has naturally encouraged a reductionist perspective, the convenient compartmentalization of resources and systems that are then manipulated and changed in isolation. Human systems are complex but function in the wider environment along relatively simple linear frameworks. Material and energy are imported whilst waste, produce and heat are exported. Current scientific and technological efforts have failed to respond adequately to the problems associated with this open-ended relationship.

The case made here is not for more scientific study or even for improvements in science but rather for a fundamental change in perspective across all levels of society including science: the adoption of a post-normal science perspective based on the insights of complex system science (see above). A post-normal science perspective uses current scientific models and theories to ask a very different set of questions on which to build scenarios and attempt adaptive solutions to problems. Rather than seek out the individual signature and behaviour of each component in a system, post-normal science attempts to understand the extent of connectivity in a system and the emergent properties manifest in this relationship. It also aims to construct probabilistic scenarios based on knowledge of the factors impacting on a system(s), and adopt a multi-scaled, whole system approach to all lines of enquiry and problem-solving. A certain degree of reductionism is inevitable. For instance, the scientific categorization and classification of nature as well as the use of metaphors and language to describe form and function set cognitive limitations on the observed physical complexity. However, without these cultural constructs there would be no means of building any form of framework.

A system can be defined by form (structure) and function, a description used for biodiversity. Function is expressed and measured in terms of thermodynamic principles, specifically exergy and entropy. The rationale for this has been explained in detail in the preceding sections but in summary, all processes and outputs are dependent on exergy, and persistence is a function of the state of entropy in the system. System form defines the spatio-temporal structure across all scales. It includes the heterogeneity manifest in 'patches' or sub-systems as well as the connectedness and connectivity inherent at genetic and trophic levels. It also includes non-living biomass. The structure or form of a system has been described using the adaptive cycle metaphor, and at the moment it is the most appropriate model for representing inter-connectedness between holarchically arranged meta-systems. These properties can be measured using structural indicators such as biomass and connectivity (Jørgensen 2006). Inevitably, indicators for form and function of a system converge towards a unifying predictor set of measures for ecosystem health—the basis for ecosystem theory.

Natural ecosystems continue to evolve to avoid collapse towards entropy, and this involves the building of complexity into form and function. Ecosystems that appear to demonstrate all the characteristics of a self-ordering, holarchic organization (SOHO) (Kay 2008) can be described as ***"ideal-seeking systems"***, and the best examples of these are likely to be found in "un-trammeled" landscapes, areas that have escaped human disturbance and alteration. Large tracts of "free-willed" ecosystems serve two vital roles, namely, the provision of ecosystem services to the wider landscape; and also as a baseline or template for the sustainable management of modified areas. Currently, about 12% of the earth's major ecosystems are protected from development, however, many of the protected areas are far from representing free-willed ecosystems, and the protected area system alone has not prevented the continued decline in global biodiversity and ecosystem degradation caused by human development. Most of Earth's biodiversity exists outside these areas in the used landscape. This situation is unlikely to change in the future, in fact, conditions can only get worse under the current scenario of "business as usual." To tackle problems of this magnitude and complexity a framework for sustainable development is needed that operates to optimum indicators for ideal-seeking systems based on non-equilibrium thermodynamics and complex systems theory. Guidelines for sustainable development indicators are set out in the following section.

INDICATORS OF SUSTAINABLE DEVELOPMENT

Energy, exergy and entropy

Energy and exergy are the drivers to system evolution and persistence. The dissipation of energy through a complex system may be difficult to track and measure but it is possible to record with reasonable accuracy the amount of incoming and outgoing energy. These two end points to energy transformation provide information about efficiency, state of entropy, and exergy capacity within a system. This strategy applies the "**black box principle**" that is to say, there are unknowables in the system (uncertainties) but these do not necessarily hinder the process of systems accounting and management (Fig. 1.). In most forms of industry, productivity and performance have traditionally been measured in terms of energy efficiency. More recently, these same measures have been applied to wider social infrastructures including domestic lifestyle. However, energy flow does not necessarily offer the most appropriate context for sustainable development and a more specific means of accounting and tracking is needed. Exergy is a more realistic form of assessing performance and behaviour in human systems. By focusing on the availability of usable energy (exergy), greater emphasis is put on the development of semi-closed systems that conserve and recycle energy and materials. For instance, the clustering of industry to minimize waste output by re-using by-products as alternative energy sources, "one industry's waste is another's energy." In semi-closed systems that recycle energy and material, it is much easier to budget energy use and also to construct working models for exergy capital and feedback mechanisms.

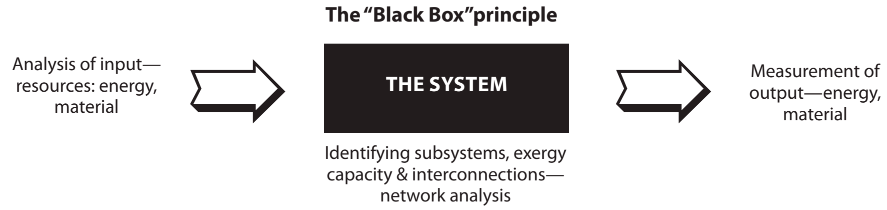

FIGURE 1: The blackbox principle in systems analysis.

It is more difficult to apply this form of energy accounting in large open landscapes where the exchange of energy and materials with the surrounding environment is unconstrained. In more industrialized regions of the world, a sophisticated grid system of energy budgeting and distribution operates to regional scale. However, they do not factor in substantial exchanges of energy that pass through rural or natural landscapes, or the losses of material and energy that result from land use change and management. What is more, changes in status of any one sub-system will trigger a cascade effect on others that may result in a release of energy and material. Therefore, we can expect on-going shifts in exergy capital across sub-systems. To address these issues it is essential to work to a holistic framework such as ecosystem services analysis. This process uses network analysis to reveal as many of the inter-relationships and pathways between meta-systems and their components. For instance, in agricultural landscapes surrogate measures of energy input-output would include accounting of fuel and material consumption together with the assessment of plant/animal productivity (biomass build-up), and final agricultural product output, energy storage and expenditure. This is a rather simplistic approach that would need refining to include a more complete network analysis to take account of the remaining biomass (part of the exergy capital), proportion of recycling of material and energy, and the extent of connectivity—the biodiversity. Similar forms of assessment would be carried out for river and wetland systems, forest landscapes, grasslands, mixed cultural systems amongst others. An effective assessment of the sustainability of a system would include an ecosystem mapping exercise and the use of a predictor set of complementary proxy indicators.

Such a predictor set would comprise an ecosystem services map—a network analysis for the holarchic system together with a range of proxy measures for ecosystem efficiency. These could take the following form:

- Quantity of energy input and utilization
- Exergy capacity (stored, usable energy in the system + carbon storage—resource banking)
- Positive feedback measures (quantity of non-recyclable energy and material—waste material and heat loss/capacitance)
- Connectivity/connectedness (biodiversity)

An ecosystem services assessment ‘map’ would provide a near-enough approximation of the structure and inter-relationships between the components of a system as well as the pathways between the different meta-systems in the larger holarchic construct. The ecosystem services ‘map’ constitutes the spatial representation of the adaptive cycle concept model. Energy and material dissipate within the systems and also move along the pathways between meta-systems. The quantity of energy and material that ends up as stored carbon (living and dead) together with the amount that is lost to heat (irreversible) is a function of exergy capital. These measures as well as aspects of biodiversity (diversity and functionality) indicate the level of sustainability in the system.

Biodiversity as a proxy measure of sustainable development

Healthy ecosystems contribute to the well-being of humanity, and the Convention on Biological Diversity calls upon member states to conserve and sustainably use biological diversity. The emphasis is characteristically anthropocentric and often focuses on the short-term consumption and extraction use value but understates the ecosystem functioning and services that are the life insurance of life on earth. It is understandable how ecosystem services and bio-commodities attract the interest of the commercial world; after all, you can’t put a price on the intrinsic value of nature. That said, the message repeated in the Convention for Biological Diversity is emphatic, the planet’s lifeline rests in biodiversity.

It is impossible to account for all biodiversity or to reduce the multidimensional concept down to a single formula or number (Purvis & Hector 2000). The current description of 1.75 million species worldwide more realistically represents 10% of the total. In fact, the rate of discovery of new species suggests an even higher figure than this (Purvis & Hector 2000). Uncertainties about biodiversity are complicated by estimates of species loss to the impacts of human development. Wilson (1992) used species-area relationships to derive an annual extinction rate of 27,000 species. The effect of this biodiversity loss on ecosystem function is less clear although there is mounting evidence to indicate that there is a strong connection between biodiversity and ecosystem function. For instance, diverse communities are more resilient and resistant to invasions (Stachowicz *et al.* 1999). Specifically, diverse plant communities exhibit a greater variety of positive and complementary interactions (Tilman 1999). Work by Zhang and Wu (2002) on vegetation dynamics suggests that the influences of structure and self-organisation of vegetation will affect the thermodynamic nature of an ecosystem, which in turn, will relate to the efficiency and stability of ecosystems.

Changes in structural attributes of vegetation generate unique spatial and temporal responses in various microclimatic variables including temperature, humidity and light (Zheng *et al.* 2000). Increased light and moisture conditions as a result of changes to vegetation structure can promote abundant growth of plant species as well as provide favourable habitat for some small mammals (Brookshire & Shifley 1997). However, human disturbance patterns that result in substantial losses or simplification of forest vegetation will cause noticeable changes in local temperatures (Chen *et al.* 1999, Heithecker & Halpern 2006). Jørgensen *et al.* (2000) suggest that the physical-biological structure, increased network linkage between components, and the increasing replacement of r-strategy species by K-strategy organisms are signatures of evolving ecosystem complexity.

In both terrestrial and aquatic systems the primary producers are the fundamental building blocks to biodiversity, ecosystem function and resilience. In adopting this pretext it is plausible to propose a predictor set of biodiversity indicators of sustainability to complement thermodynamic indicators. The proposed indicators are as follows:

- Biomass production/carbon storage
- Diversity of native primary producers (species richness)
- Diversity of plant growth forms (functional groups, strategic types)
- "Trophic tree index" the number of functional groups of fauna and flora.

Reducing biodiversity down to a small set of surrogate measures is a blunt tool to apply to sustainable development, but if it can be demonstrated that there are clear correlations between the different elements of biodiversity and these indicators then it offers an effective and measurable technique for sustainable development. Environmental indicators are only effective when applied using benchmark standards, and these are based on conditions prevailing in 'free-willed' landscapes. These untrammeled landscapes are a vital component to sustainable development, and in this instance they provide important reference sites for the effective management and restoration of cultural ecosystems.

The current debate on wilderness continues to raise contentious philosophical and ethical issues between the preservationists and the "utilitarianists" and yet the case for protecting wilderness can be made from both perspectives. Free-willed landscapes provide an essential practical function to global ecosystem function; consequently, we have a moral obligation to ensure that they are protected from human impact. The important question is how much wilderness can we afford to preserve and do we practicably need to ensure global sustainability. This presents us with the conundrum of balancing usable natural capital with environmental buffers—ecological legacies retained in a natural state for the ecosystem services they provide. There is no final answer to this question as change is inevitable and with it comes uncertainty and indeterministic tendencies, and it is impossible to generate "end-point" objectives and goals for moving targets. In such cases, the logical answer is to conserve as much wilderness as possible, and some more, applying the precautionary principle.

In summary, a predictor set of optimum indicators for sustainable development comprise a combination of non-equilibrium thermodynamic and biodiversity measures. These are based on benchmark standards drawn up from observations and studies of conditions in free-willed landscapes. Establishing a base line and benchmarks for sustainable development provides a pathway for the next stage of building a strategy around the principles of ecosystem theory, drawing on principles of non-equilibrium thermodynamics and complex system theory.

PREDICTOR SET OF OPTIMUM INDICATORS FOR SUSTAINABLE DEVELOPMENT BASED ON BENCHMARK STANDARDS TAKEN FROM REFERENCE SITES—FREE-WILLED LANDSCAPES

Non-equilibrium thermodynamic indicators
- Quantity of energy input and utilization
- Exergy capacity (stored, usable energy in the system + carbon storage—resource banking)
- Positive feedback measures (quantity of non-recyclable energy and material—waste material and heat loss/capacitance)
- Connectivity/connectedness (Biodiversity)

Biodiversity indicators
- Biomass generation/carbon storage
- Diversity of native primary producers (species richness)
- Diversity of plant growth forms (functional groups/strategic types)
- "trophic tree index" the number of functional groups of fauna and flora

2.3.3 GENERATING PRACTICAL MODELS FOR SUSTAINABLE DEVELOPMENT USING PRINCIPLES OF POST-NORMAL SCIENCE

A holistic systems approach to sustainable development describes a fully interrelated, cross-scale strategy for the long-term procurement of the optimal survival of the human species. In their proposal for a systems approach to *strategic sustainable development (SSD),* Robèrt *et al.* (2002) advocate a macro socio-economic policy that is built on an ecological platform. This idea (sometimes referred to as biomimicry) is not new but there is little evidence for significant practical development in this field. Furthermore, attempts at developing strategic sustainable development often ignore fundamental issues to do with scale and indeterministic tendencies, two key attributes of ecosystem dynamics. For instance, current structures for macro socio-economics are unsustainable because they are too open, are resource-hungry, and too inflexible to patterns of unpredictable change. Consequently, wastage of resources, boom-bust cycles, and regime instability or collapse are common features of most socio-economic systems around the globe. In just a few cases, typically, in societies that exist at the boundaries of environmental tolerance, there are some good examples of biomimicry, including energy and material recycling, principles of carrying capacity, and adaptive strategies to unpredictable change. However, they do not represent the norm as most of these societies survive in small numbers, in some cases, nomadic 'bands' moving across large tracts of landscape. New working models are needed to resolve problems associated with over-sized and increasing populations.

In ecosystem models the socio-economic infrastructure is nested within the larger holarchic construct of the natural system. This sets clearly defined limits on human population growth and utilization of energy and natural resources. It also requires a complete re-adjustment of the design and management of cultural landscapes to minimize the loss of ecosystem complexity, structure and biodiversity, and to maximize thermodynamic efficiency. Such a strategy requires synchronicity with natural feed-back systems, disturbance regimes, and space-time heterogeneity. Management practices must adopt adaptive and pro-active strategies that factor in environmental uncertainty. In conservation, this requires a shift away from human activities and systems that promote the status quo and steady state to those that create flexibility and adaptive resilience.

WORKING WITH LANDSCAPES

A multi-scaled approach to landscape management would apply principles of landscape ecology, specifically, two models: namely the patch-corridor-matrix model (Forman 1995) and the continuum model (e.g., Fischer & Lindenmayer 2006). Both provide appropriate metaphors for the required territorial design and management strategy of landscapes. At the largest scale, the new strategy would involve the retention of substantial tracts of untrammeled functional ecosystems, including marine, forests, peatlands (tundra), wetlands and mountains, a form of "ecosystem banking". These systems would provide the necessary insurance against catastrophic changes by securing the sources of biodiversity evolution and macro-environmental services. The scale of protection of these systems would be set by probabilistic models using both non-equilibrium thermodynamic and biodiversity indicators. For instance, empirical measures of thermodynamic conditions, and carbon storage at regional and global scale would give some indication of the specified limits for both core and buffer zones.

The pressures on land use of a growing population have led to the inevitable loss, fragmentation and degradation of ecosystems. This trend is unlikely to change in the near to mid future and thus calls for radical alternatives to current practice across all cultural landscapes. A number of existing initiatives, for instance, the pan-Europe strategy for biodiversity that includes Natura 2000, and the Emerald Network, provide practical models for mitigating against the effects of human impact on the natural environment. These schemes involve the conservation and creation of large green networks or corridors between protected areas or centres of biodiversity. However, the political will to fully implement eco-corridors across the region is weak. Hopes of developing a similar effective globe-wide strategy are unlikely without changes to policy. To succeed this scheme would require full integration into a larger spatial planning strategy at ecoregional, national and international levels. Specifically, it would target natural corridors such as hill ranges, altitudinal corridors from lowlands to the high mountains, riparian systems, forests and wetlands[55]. The size of these corridors would be proportional to the natural dynamics of the system. An example of large scale integrative design and planning is evident in the recent European Water Framework Directive strategy for the management of river catchments. It incorporates all systems that relate to the hydrological regime. Once more, this system management must be integrated into wider spatial strategy plans that include other complementary system strategies for biodiversity, forestry, and urban and rural planning. A combined synthesis of network analysis and ecosystem services across all meta-systems would provide the framework for fully integrated operational objectives and action.

The spatial realization of a fully integrated complex systems management strategy would typically appear hierarchical as well as highly variable in pattern and configuration (Fig. 2). Large tracts of self-willed ecosystems would abut cultural landscapes of varying degrees of modification but diffused with more natural ecosystem outliers and an intricate network of eco-corridors. Furthermore, practices of adaptive management in cultural landscapes would generate plasticity in the system with variable patch dynamics. At a finer scale, the retention of environmental legacies including flood plains, rank vegetation, coarse woody debris, scrub, wet flushes, ponds, wild populations, and others are an important element of maintaining permeability and functionality in modified landscapes. More natural disturbance patterns and succession dynamics in outlier patches will contribute to the wider environmental sustainability of the modified landscape.

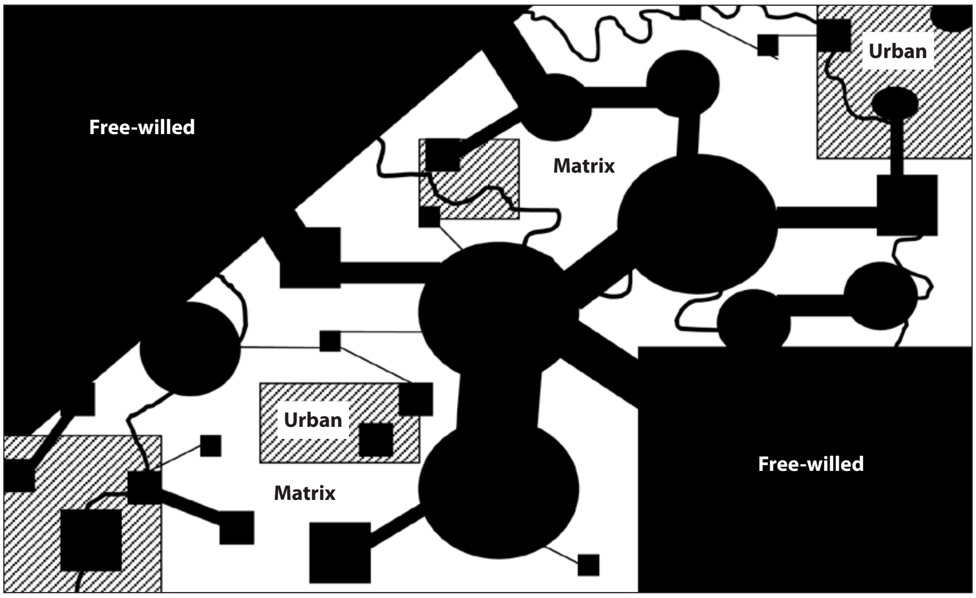

FIGURE 2: Schematic model of free-willed ecosystems with outliers and corridors.

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[55] In Bolivia, in the context of various conservation exercises on the national and sub-national scale, the combination of conventional targets of conservation planning (applying a fine-filter approach that identifies areas relevant for species richness and endemism as well as a coarse filter targeting ecosystem representation) and function and process-representing targets, such as mountain ranges, blocks of intact forest, or altitudinal corridors, has led to interesting results informing integrated conservation and development initiatives (Ibisch et al. 2002, 2006, 2007).

ON A SOCIAL FRAMEWORK FOR SUSTAINABLE DEVELOPMENT

Achieving sustainable solutions is also about engaging with social values and individual behaviour. In the current business as usual scenario most of global natural capital is traded and valued on an economic basis. This system imposes strict constraints on valuing the true worth of biodiversity to human survival and well-being as economic measures are not necessarily the best indicator. Existing 'life-value' references such as biodiversity, environmental mitigation, nature-worth, life-quality indicators and well-being could be evaluated using a range of non-market value approaches. For instance, a benefit transfer system can use economic information for a particular place and time to inform policy makers about the economic value of environmental goods and services at another place and time (Wilson & Hoehn 2006). Economic worth is either measured in monetary units or as value functions that are based on original value data or metadata (Loomis 1992, Woodward & Wui 2001). Such values, "vector values", can be derived from statistical evidence of services value, a form of environmental accounting of stocks and flows (carbon storage and transfer and exergy capital would be examples of vector values). As such, they could be traded and banked by organisations and governments operating to novel bio-economic structures and regulations.

Science and technology should re-focus efforts towards ecocentric innovation, methods of working towards ideal-seeking systems' using principles of thermodynamics. Thermodynamics can be used to greatly improve energy utilization and other systems. Exergy analysis provides the means for designing more efficient energy systems by reducing inefficiencies (Dincer & Rosen 2004). Energy efficiency and critical minimization of artificial or toxic residues is a core principle to industrial ecology, and industrial ecology models can be effectively worked into strategic sustainable development (von Korhonen 2004).

Fundamental to this change is the reform of neo-classical models of economy by embracing principles of ecological economics (compare Ibisch *et al.*, A.2., Ibisch & Hobson, B.2.2., in this document). Gross Domestic Product (GDP) is no longer an accurate or appropriate measure of a nation's prosperity and an alternative way of measuring social development is required that forces change to existing performance indicators (Jackson 2009). Human endeavour and prosperity should be evaluated using criteria that define capacity building in communities; meaningful work; and participation in society or creative endeavour (Jackson 2009). This requires a paradigm shift in social logic away from a commodified world to one that is based much more on human-centric values—participation, education and social cohesion. Under this system the economic domain is recognised as part of the biosphere and as such is based on infrastructural capital rather than natural capital. Ecological economics rejects the proposition that natural capital can be substituted for anthropocentric capital derived through the relentless pursuit of resource-hungry technology. Furthermore, the concept factors in irreversibility of environmental change, uncertainty and intergenerational equity. It is rather more adaptive to indiscriminate changes, relying on agent-based modelling techniques that recognise the value of 'self-organising systems.' This micro-system approach is complemented by macro-scale systems thinking that operates a holistic approach to deal with socio-economic interests. The validation of the ecological economics model is underscored by the primary objective, which is to ground economic thinking and practice in the laws of thermodynamics. Success, goals and outcomes are no longer exclusively measured in monetary worth, but also by using relative valuation and environmental accounting—biological and physical indicators of worth—a form of 'biodiversity financing.'

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