Int. J. Water, Vol. 5, No. 4, 2010 353

Losing fertile matter to the sea: How landscape entropy affects climate

Wilhelm Ripl

Department of Landscape Ecology, Limnology,
Technical University of Berlin,
Nuthestrasse 4A, D-14513 Teltow, Germany
E-mail: w.ripl@allianz-der-kommunen.de

Abstract: Under natural conditions order is created by interactions between water, temperature, chemical gradients, ground surface, and organisms. However, in the 'developed' landscape, order is replaced by randomness. The de-coupling of energy and water cycles is observed in eutrophication, as irreversible matter losses break closed metabolic cycles in coenotic structures. Another cause of landscape entropy is the lowered water table, which decreases surface flows. Applying the Energy-Transport-Reaction Model to the River Stor Catchment in Germany, the paper shows how dissipative structures balance terrestrial and aquatic ecosystems, returning short water cycles to the atmosphere. This ecosystem integrity benefits food production as well as climate.

Keywords: landscape; water–energy coupling; vegetation; short water cycle; climate; sustainability.

Reference to this paper should be made as follows: Ripl, W. (2010) 'Losing fertile matter to the sea: How landscape entropy affects climate', *Int. J. Water*, Vol. 5, No. 4, pp.353–364.

Biographical notes: Wilhelm Ripl has worked internationally on control processes in aquatic ecosystems, the development of restorative measures for lakes, and, following Prigogine's work on feedback, a comprehensive theory of the self-organising landscape. He graduated from Lund University and was for many years Professor of Limnology and Landscape Ecology at the Technical University of Berlin. He retired 2003 and is now Scientific Manager of (SAT) Systeminstitut Aqua Terra e.V., a Berlin-based consulting group. He has some 250 publications, scientific reports and project documentations, including 'Water: the bloodstream of the biosphere', *Phil. Trans. R. Soc.*, London (2003).

1 Human impacts

To understand the causes and consequences of landscape degradation, it is necessary to see wetlands, lakes and rivers as integrated parts of a whole catchment area. Rain, initially condensed water vapour, is the dynamic transport, cooling and reaction medium, which collects in the lowest parts of the landscape. Water in lakes and rivers reacts to the local atmosphere and landscape. Many processes have to be considered to understand how human impacts in a catchment can undermine its sustainability.

Long-term anthropogenic influence on the landscape has affected the water cycle and its coupling with solar energy flows. With the deterioration of local short water cycles – rain, plant evapotranspiration, cloud formation and rain – climate instability can become severe, as less water is available for cooling. Temperature gradients thus become steeper and more randomly distributed throughout a catchment. The restoration of short water cycles in the landscape is as essential for climate mitigation as it is for sustainable human societies.

Landscapes, including catchments, lakes and rivers, reflect historical water processes in interaction with the geogenic substratum, vegetation cover and human societies. Lakes and rivers are thus indicators of past and present dissipative processes (Björk, 1970). Under natural conditions, matter is held in place by closed metabolic cycles; but their deterioration causes irreversible matter losses, decreasing landscape efficiency (Ripl and Ridgill, 1995).

In the glacial epoch, lakes developed from a mesotrophic state as long as a flow of material from the water catchment was maintained (Digerfeldt, 1972). During the establishment of primary vegetation cover, when terrestrial matter cycles were still poorly developed, matter losses from land to water were relatively pronounced. However, with the evolution of terrestrial biodiversity, landscapes increased in metabolic and thermodynamic efficiency and decreased in ageing. In the littoral zones of lakes and rivers, short matter cycles were established by coenotic structures like periphyton preventing runoff and sediment loss.

Over the past two centuries of industrialisation, random has altered the distribution of human settlements and vegetation cover. In landscapes, lakes and rivers, the ageing process or entropy has speeded up as dissipation of the solar energy pulse is compounded by the human use of fossil energy sources. The effect is to randomise the time and spatial pattern of thermodynamic processes in the natural landscape. In addition, emissions from industrial facilities using coal or oil produce acid forming nitrogen and sulphur oxides, which create plant die-back.

In terms of food production, self-organising landscape processes are replaced by agricultural practices oriented towards net output. Vegetation cover has been cleared, sub-surface water tables have been depleted and organic soil layers mineralised. The feedback control process of the water table through plant evapotranspiration has been interrupted. Thus, a short-term net productivity is gained at the cost of long-term landscape ageing.

As people adopt an urban industrial consumer lifestyle, the complex natural recycling of organic nutrients in the landscape is replaced by the simple elimination of base cations to the sea as waste. Removal of phosphorus and nitrogen takes place in energy-demanding sewage treatment plants. As sewage is polished by precipitation of phosphorus with metal ions, nitrogen rises to the atmosphere by de-nitrification, while minerals are discarded in ocean outfalls.

Human activities such as the unlimited growth of cities, industrialised agriculture using fertilisers, pesticides and irrigation, and forestry based on clear cuts and fast-growing monocultures undermine and randomise inherent landscape controls. The effect is seen in sedimented lakes, heavy with plankton, indicating the failure of ecosystem efficiency. As interlinked, short-circuited organic production and respiration processes are separated in time and space, entropy and landscape ageing set in.

Eutrophication is a common by-product of urbanisation and industrial agriculture, which pollutes rivers and lakes with nutrients and effluent. The base cation flow from many continental areas exceeds 500 kg of $CaCO_3$ equivalents per ha and year (Ripl et al., 1995). The nutrients and minerals lost to agriculture are now replaced by artificial fertilising agents such as nitrogen, phosphorus and base cations such as calcium, magnesium and potassium. The human drive to increase net productivity in forestry or agricultural sites means an increased proton flow in root zones and irreversible losses of buffer substances and nutrients with water runoff. In impoverished soils, productivity decreases due to the higher energetic outlay of stressed plants.

The intensified turnover and mineralisation of the root biomass enriched in sulphur and nitrogen compounds has an acidifying effect on the soil, releasing mineral ions, eventually washed away in rain (Ripl, 1995a). In littoral zones, the protolysis of water caused by metal ions (such as Al and Fe) decreases the buffering capacity of lakes, resulting in acidification and randomised coenotic structures. The reproduction cycle of fish dependent on littoral food chains is thus endangered (Appelberg et al., 1993).

2 Energy-Transport-Reaction Model

The theory of energy-dissipative structures as developed by Prigogine (1988) refers to nature as an energy-dissipative process, and to the structure of organisms and ecosystems as the result of this dissipative process. New, temporally stable structures evolve far away from thermodynamic equilibrium as a necessity and not by chance. This theory closes the gaps between physics, chemistry and biology. Together with the ETR Model, it can explain the self-organisation of ecosystems in a delimited area under precise alternating energetic conditions according to sustainability criteria.

For researching the open field, a theoretical understanding of energy-dissipative processes is essential for the accurate modelling of landscape functions. The spatial and temporal distribution of dissipative structures in the landscape is determined by energy in interaction with water. The incoming solar energy pulse is partitioned and dissipated by water in three processes – physical, chemical and biological.

The landscape changes outlined in the first section of this paper were arrived at through a deductive normative ecosystem model, which shows eutrophication and acidification as consecutive problems inherent to the energetics of the system as a whole. Such a hypothesis can be corroborated or falsified by observation of data over time and space. This heuristic is more promising for understanding landscapes than models generated statistically from discrete ecosystem data. A reductive approach to research on, say phosphorus, leads to linear models with little chance of restoring complex dissipative interactions that occur in land or water bodies.

For example, energy- and resource-intensive sewage treatment plants are merely a short-term solution for eutrophication and cannot stop the landscape ageing process. European studies show landscape ageing by a factor of up to 100 compared with entropic randomisation in natural coenotic structures (Ripl et al., 1996). Retrospective efforts to protect water will inevitably result in increasing ecological and economic costs.

The areal functionality of physical nature necessary for the sustainability of human societies rests on:

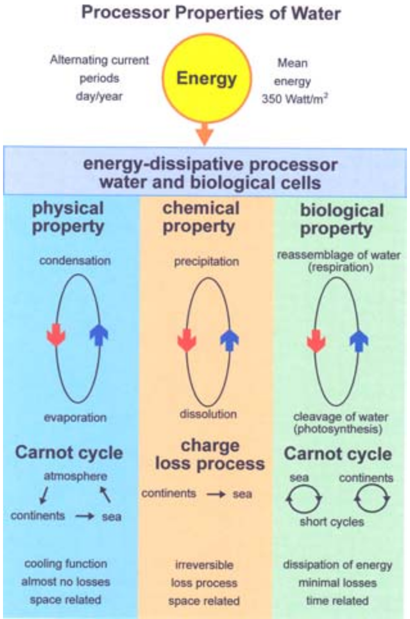
- the integrity of the water cycle and its distribution
- the integrity of atmospheric composition and its vertical distribution
- the integrity of the cooling system and the areal temperature distribution
- the integrity of process and reaction patterns and distribution in time and space
- the integrity of the living membrane, which protects soil fertility from toxic contaminants.

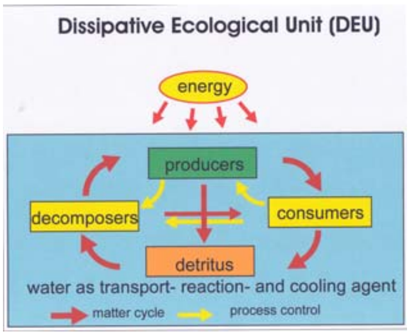
The holistic approach considers all of these landscape processes and their coupling in space and time. Unless interlinked landscape functions can be restored, loss of vegetation cover and large-scale acidification will destroy the water cycle and the world's most important cooling system.

The interrelation of energy, water transport, physical, chemical and biological processes are described in the ETR model (Ripl, 1991, 1992). Ecosystem functions are optimised as dissipative energy processors, through the water cycle, driven by precisely structured, cyclical additions of energy.

As noted, the input of fossil energy associated with heavy transport has resulted in excessive energy and matter flow densities. Degradation of coenotic structures and distortion of the water cycle has resulted in a major loss of cooling properties and their distribution (Ripl, 1991, 1992). The out-of-phase oscillations create random perturbations in natural systems, increasing the probability of floods and droughts, temperature extremes, abnormal tropospheric reactions, mass die-off of plant and animal communities.

The water cycle is the basis of all metabolic processes in nature. Water is the connecting and reaction medium of the biosphere and its structures in space and time. The dissipation of energy by the water cycle is driven by solar radiation. Water and living organisms as processors channel, partition and dissipate energy.





Water, as an energy processor, shows three dissipative properties acting in a recursive way, all three of which involve both cooling and heating. These three properties are the physical process of evaporation and condensation, the chemical process of dissolution and precipitation, and the biological process of production and respiration and each implies water cleavage and reassembly.

3 Water as dissipative structure

Physical processor property (evaporation-condensation)

The daily solar energy pulse activates the most important dissipative medium, water, to dissipate the pulse in space and time. Energy potentials are mainly distributed by evaporation and condensation of water using the enthalpy leap between liquid water and water vapour or ice, respectively.

Chemical processor property (dissolution-crystallisation)

The chemical processor property of water is based on the polar property of the water dipole, which leads to the dissociation of water. This dissociation lets water act as a weak acid with a proton density of 10^{-7} mol/l at 20°C. Chemical reactions at an interface with solid matter are thereby enabled, leading to dissolution of various ionic lattices into dissolved ionic charges. At thermodynamic equilibrium, the process ceases. This processor property causes an irreversible charge flow, due to dissolved matter in soils and its transport by water to the sea.

Biological processor property (photosynthesis-respiration)

Efficient dissipative water-structures containing highly structured organic molecules can absorb and channel light energy in such a way that the water dipole is disintegrated (condition at $pH = 0$). The liberated hydrogen then reduces carbon dioxide, forming carbohydrate radicals and finally sugars, starch or cellulose, while oxygen is liberated to the atmosphere and environment. This kind of dissipative structure is found in primary producers such as photosynthesising plants.

The opposite reaction is known as respiration whereby water is reassembled thus producing energy for coupled biocatalysed processes. Since these processes bound to organisms keep matter cycles in place, areal losses in dissolved matter are rare (Ripl et al., 2004). Organisms in ecological communities form coenotic structures decisive for the short-circuited evaporative water cycle. A stock of energy is stored in the form of organic degradable matter and nutrients and minerals or soil stable in their spatial domain. These sustainable structures dissipate the solar energy pulse in time and counteract matter losses via the hydrological process and chemical reactivity.

Irreversible matter losses from a catchment determine the stability of the ecological assemblage of organisms in interaction with their energy processor structure. The metabolic efficiency of such a structure, its coenosis, coupled with the dissipative water cycle, is given by the amount of matter cycled in relation to matter or charge losses for a given amount of energy delivered.

The least ageing or most closed structure with highest thermodynamic efficiency is one in which the least irreversible losses will prevail. This suggests that evolutionary selection of new species operates to improve ecological efficiency by minimising ageing. A mature system is characterised by more species than a recent system. However, high species diversity does not necessarily indicate a sustainable system. The diversity concept is, therefore, implied in the sustainability concept, but as a stand-alone concept it is redundant to the sustainability concept.

Coenotic structures are analogous to an electronic circuitry of various components and they can be ascribed a certain coefficient of thermodynamic efficiency in a given environment (Ripl, 1995a). Organisms like energy processors dissipate an energy pulse, converting it into an even matter flow by reducing energy flow density. The usable energy is converted to mean temperature in time and space lacking further potentials for directed, i.e., non-random processes.

The physical, chemical and biological processor properties of water allow five necessary, functional components to assemble a simple ecosystem, delimited in time and space. The five functional components of an ecosystem are:

- *Primary producers* as process carriers and process controllers have a double function. As process carriers, they produce carbohydrates and biomass and store energy, providing an energy source independent of the solar pulse. As process controllers, they pump water through the soil, organisms and atmosphere by evapotranspiration. Thereby, the water content in the soil is controlled, as are redox conditions and mineralisation.
- *Detritus* as a raw humus layer and soil containing the nutrient, mineral and energetic stock.
- *Decomposers* such as bacteria and fungi are process carriers responsible for the mineralisation of detritus. They can be activated by water flow and stopped when water flow ceases by negative feedback due to product inhibition and low redox potential. These components can clog the interstitium in the humic layer due to rapid reproduction and thus increase resistance against percolation.
- *The food chain* as a process controller reduces space limitations by removing and using both autotrophic and heterotrophic or human process carriers for food, keeping the energy-dissipative system reproductive and efficient.
- *Water* as the energy-dissipative cooling, transport and reaction medium.

Such a structure shows a minimum of openness with respect to matter flow in a given energetic environment and can, therefore, be delimited in space and time. This 'rational' complex of natural structures provides thermodynamic efficiency.

4 Thermodynamic efficiency

Efficiency relates to two kinds of processes:

- Cyclic processes operating in tandem with high frequency and low emissions.
- Irreversible or sequential processes, which occur at lower frequencies with high spatial impact. These show irreversible losses of bases and nutrients to the sea – expressed in proton flow equivalents (one mol of carbon is equivalent to two protons or two equivalents of ionic charges). The losses may become cyclic outside of a relevant spatial or temporal observation span as it occurs in glaciation phases or tectonics.

Ecological efficiency, which is closely related to stability and sustainability, can be calculated when cyclic processes are put in relation to random processes, causing irreversible losses (= charge losses to the oceans = reduction of sustainability). Efficiency is considered as:

$$(P - L)/P$$

where P = gross production, L = irreversible losses all given per hectare per year. For purposes of calculation, the flow is expressed in proton equivalents as energetic units according to the pH concept. When absolute sustainability is calculated, the stock function of the mass of base cations and other nutrients has to be known down to a depth of about 1 m – the approximate depth of the active root zone (Ripl, 1995a, 1995b).

By the principle of self-organisation, the least ageing and most sustainable system has the best cycling capabilities and least irreversible material flow. It is relatively free of landscape entropy.

European research (Ripl et al., 1996) shows natural gross productivity per ha and year amounts in wetlands at a maximum to about 12 tons of carbon or 2000 kmol of protons, while irreversible losses from water courses in large European catchments average about 20 kmol per ha and year. To achieve sustainability, losses of this order would need to be compensated by about 600–800 kg of limestone/ha and year in areas used for agriculture and forestry. Total salt loss averages 1000 kg/ha and more per year.

As plant-usable soluble mineral and nutrient stock from the topsoil diminishes, less soluble material like heavy metals accumulates, along with surface active immobile organic matter, such as pesticides. As long as the water cycle is active, the selection process for material deposits proceeds according to solubility criteria.

The relations between energy flow and matter flow are highly non-linear but corroborated by sediment analyses containing large accumulations of toxic metals and residues, especially in the upper strata (Ripl et al., 1995). Fine dust particles contain more toxic substances than coarse particles. Emissions to the atmosphere occur almost exclusively from uncooled, overheated areas lacking vegetation, while cooled wetlands, lakes and rivers are the places for fall-out with precipitation.

The holistic conceptual ETR framework was applied in an investigation of the River Stör catchment carried out between 1990 and 1995. The research was supported by the Ministry of Education and Research of the Federal Republic of Germany and County of Schleswig Holstein, NW Germany. The 1155 km^2 catchment is predominantly arable (72%) with forestry (15%), and lies between 6 and 90 m asl, with a river of mean slope 0.8 m/km. The project sought to detail catchment systems and processes to derive spatiotemporal landscape measures for sustainability planning. A deductive procedure enabled rapid acquisition and interpretation of results.

The parameters included: total catchment runoff; dissolved chemical load (using both chemical analysis monthly at 128 measuring sites and conductivity measurements in 10 sites and 20 min intervals); temperature measurements (on a micro-habitat level and from satellite information); and aspects of river morphology as well as land use and geophysical map data. The results of temporal measurements on the ground were compared with relatively fine-scaled spatial information from satellite imagery.

The analysis of chemical data by means of mean and variance patterns of parameters introduced earlier allowed three classes of matter loss to be distinguished:

- Acid creators, such as sulphur and nitrogen, indicate the breakdown of organic substances. Where a water table is declining through decreased surface water flow, breakdown processes occur in upper soil layers while matter transport is reduced. With a rising water table and increased surface water flow, released mineral salts and nutrients are dissolved and easily transported. Their contribution to the dissolved load, therefore, often peaks in autumn or early winter when the water tables rises.
- Soluble ions such as calcium, potassium and magnesium indicate alkalinity. Their concentration is directly dependent on solubility and water flow. At very high rates of runoff, a rapid lowering of concentrations will be measured. Fluctuations are generally less than that of the first group.
- Elements like heavy metals and particulate phosphorus are coupled to the erosion process at the soil surface layer.

5 Matter loss and landscape entropy

- The process of matter loss is a function of area and therefore primarily dependent on available water and its distribution. Second, the matter-loss flow is determined by the energetic and solubility criteria in their spatio-temporal distribution.
- Energetic boundary conditions of the mineralisation process of organic soil particles, which control pH and redox potential, are determined by the alternation between dry and wet phases in their spatio-temporal distribution.
- Following human actions with respect to water supply, the degree of coupling between production and breakdown processes is lowered and overall ecosystem efficiency reduced. This is demonstrated by large matter losses from soil surface layers. Through such matter loss, the ratio between available, soluble material and less-mobile toxic substances like heavy metals is also changed. The habitat is degraded in a non-linear way.
- The salt concentration of the dissolved load changes in direct proportion to conductivity. Thus, a time-series of runoff salt concentrations can be derived from a monthly measurement of chemical concentration together with data obtained from an automatic recording device or conductivity probe having a very high temporal resolution (20 min).

- There exists a close site-specific link between discharge as total runoff and conductivity. The conductivity rises in response to increasing water discharge, then falls slowly.

Ecosystem efficiency can be defined by the ratio between gross production and turnover of matter to matter losses, or alternatively, through the quality of thermal damping. The River Stör investigation confirms that the primary measure for system sustainability is its efficiency, and where efficiency is high, little energy is needed to compensate for matter loss (Hildmann, 1999).

Landscape self-optimisation automatically increases sustainability and hence enhances social stability in human settlements. Nevertheless, methods of efficiency evaluation have to be taken further so as to better judge differences between regions or sub-catchments (Ripl et al., 1995).

It is not always understood that water management and protection requires the control of water and matter flow processes in the landscape as such, rather than simply the management of aquatic ecosystems.

At present, landscape entropy by irreversible charge losses amounts to approximately 20 kmol/ha/yr. Therefore, it is imperative to redevelop landscapes together with their water transport systems, to minimise this entropy. Satellite imaging shows clearly the lowered cooling capability of the landscape due to industrialisation; urbanisation; agroindustry; vegetation clearing and irreversible charge losses from random water runoff. These quantitative measures suggest a compound deterioration of the system's energy-dissipative structure. This dynamic structure controls, and is controlled by, the distribution of solar energy, potentials and water-based dissipative processes in the landscape. Changes in the atmosphere and climate are part of the same system.

Likewise, evolution and ecological succession are long-term energy-driven processes, and in confined areas like a catchment with a coherent water transport system, they are strongly dependent on system efficiency. In good landscape management, cyclic matter flow is improved and matter loss lowered, so structuring processes of distribution and coupling. Organism structures are coupled in such a way that organisms causing high losses are coupled with organisms in a different time phase. This means that local second-order cycles are built up to reducing landscape entropy.

Complexity protects sustainability. In an area with maximised growth, a single species with a given reproduction strategy is determined by space limitations. Reproduction (r)-strategy becomes a survival (k)-strategy, for species that gain coenotic efficiency. Meanwhile, matter losses are minimised from its habitat by increased evapotranspiration lowering local temperatures. Self-optimisation relies on highly structured energetic pulses stable in frequency, phase modulation and amplitude.

6 Rational action for sustainability

What follows are some suggestions for the prevention of landscape degradation problem in catchments and water bodies. More comprehensive solutions are required to re-stabilise the effects of urban–rural integration, damaged local water cycles, unsustainable food production, and to balance of natural, terrestrial and aquatic ecosystems (Ripl, 1995c).

Still waters lose little organic matter, nutrients and mineral substances and are conservative, whereas running waters, especially water percolating through the soil, is far more erosive. Only the biological process offered by vegetation cover can control the ratio between evaporation and runoff. With increasing spatial and temporal interaction of organisms – complexity – net production decreases towards zero, carrying capacity for organisms rises, and both thermodynamic efficiency and the lifespan of the ecosystem are increased. Human societies benefit from ecosystem efficiency.

The global climate is changing due to human interference with nature. However, the models and explanations of global warming used by the Intergovernmental Panel on Climate Change (IPCC) tend to oversimplify the science involved. The phenomenon of energy dissipation, basic to all kinds of movement and process in nature, is neglected and climate change is mainly ascribed to emissions of CO_2 and methane. Global temperature targets are being suggested without a thorough analysis of all variables involved. The dissipation of energy means an energy flow from objects with higher temperature to objects of lower temperature in space and time, damping all kinds of mechanical movement at ecosystemic and atmospheric levels. Selling CO_2 emission certificates or putting CO_2 into the ground are not ecologically informed policies.

The fact is that what are called greenhouse effects never occur in open dynamic atmospheric systems, instead temperature differences are dissipated as mechanical wind or water movement. Reductive models of climate change based on the premise that radiation in is equal to radiation out is far short of the mark. It is an oversimplification of life processes, potential energy, water and matter cycles, and the nature of dissipative energy as interactions between matter creating time and space.

To achieve a sustainable water cycle, capable of re-coupling with energy flows, the following steps should be involved at catchment level.

- The use of groundwater should be avoided at all times. Lowering the water table and increasing the unsaturated soil zone not only decreases surface water flows essential for cooling evapotranspiration, but also increases irreversible matter transport to the sea, thereby reducing landscape fertility.
- Redevelopment should aim to cover upper catchment areas with unmanaged mixed forest, since the upper parts of the catchment are most sensitive to soil leaching by runoff. Forest will provide local cycling of matter and prevent erosion (Kravcik et al., 2008).
- Wetlands in headwater areas can act as hydrological buffers and equalise uneven flow rates. Hydrograph control can be achieved by building up water retaining organic soil structures and saving water even from minor precipitation events (Kravcik et al., 2008; Ripl et al., 2004).
- Vegetation-covered riparian zones store humidity, reduce mineralisation and matter efflux. These wetlands increase evapotranspiration and accumulate organic soil. In long-term management, such soils could be re-used in other areas where soils are degraded (Ripl and Eiseltová, 2009).

- Human body wastes separated by vacuum toilet systems can after digestion and with the addition of lime constitute a high-grade fertiliser for agricultural or gardening purposes. Biologically treated sewage or untreated grey water can be used in managed wetlands. This is more advantageous than energy-demanding high-tech treatment plants, producing unusable sludge and water low in nutrients but rich in bases and buffer substances. Wetlands have been identified as efficient nitrogen sinks in the landscape. Water from treatment plants is up to now irreversibly transported to lakes and coastal waters. Manure from industrial animal production is, however, still considered as fertiliser and often spread on the fields to the edges of water bodies, despite its acid and eutrophication property. The biomass produced in managed wetlands can be transformed into food for animals, to artificial soil like the terra preta developed by traditional Amazonian peoples (Pieplow, 2008), or used as an energy source.

It is important to re-instate evaporative cooling structures wherever possible, especially in cities, where storm and grey water can feed local evaporating wetland vegetation. Other evaporative structures can be incorporated into building design. Vegetative greening or water-cooling overheated urban surfaces can inhibit the transport of radicals and noxious gases to the atmosphere.

In terms of political and economic feasibility, the counter-entropic ecological functions performed by landscape managers need to be recognised proportional to their public contribution. These workers are responsible for maintaining a complex of natural engineering services – ensuring clean water goes into to rivers and maintaining a better distributed hydrograph; improving the areal cooling system through a balanced distribution of vegetation; production of energy; food; drinking water and taking care of biologically treated wastes. Hands-on ecosystem managers should be paid for improvements to their own lands and adjoining catchments.

The intelligent management of catchments through the careful use of vegetation in wetlands and food production is the only way to achieve sustainable development and counteract climate change. Funds for areal managers could be redirected from money spent on planning bureaucracies or old style industrial water engineering programmes. Additional funds could be derived by taxing polluters like heavy transport on a user-pays basis. Internationally, the time and skills of organic farmers and foresters are invaluable, as they control landscape entropy, retaining matter in catchments and regulating climatic temperatures.

Long-term human impacts on the landscape have broken the coupling of energy flows with the water cycle and this is a major influence on climate instability. At the same time, an economic reproduction or r-strategy of ever-increasing market expansion must be replaced by a survival k-strategy based on a rationally understood humanity-nature metabolism.

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