Sustainable land management by restoration of short water cycles and prevention of irreversible matter losses from topsoils

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ABSTRACT

Sustainable land management requires that water and matter (nutrients and base cations) are efficiently recycled within ecosystems so that irreversible losses of matter from topsoils are minimised. Matter losses are connected to water flow. The division of water into evapotranspiration that is loss-free, and seepage to groundwater or surface water flow that both carry material losses, is decisive in determining total losses of dissolved matter in a given catchment. Investigations of areal matter losses confirmed the instrumental role of vegetation cover. Areal matter losses measured in agricultural catchments in Germany were on average between 1–1.5 tons of dissolved matter per ha per year, i.e. some 50 to 100 times higher than those from unmanaged land in a virgin forest. Such high losses continuously reduce soil fertility and can hardly be compensated by fertilisation. Some suggestions on how to achieve sustainable management of agricultural land and maintain high soil fertility are presented – the priority is to close water and matter cycles through the incorporation of more natural vegetation cover into our landscapes and to restore the energy-dissipative properties of ecosystems.

Keywords: agriculture; energy dissipation; irreversible matter losses; soil fertility; sustainable land management; water dynamics

Sustainable land management requires both a clear definition with respect to the physical land system and a radical shift in our perceptions, our thinking and values. In physical terms sustainable development is a matter of resource economy. The ability to recycle water and avoid irreversible losses of matter (nutrients such as nitrogen, phosphorus and potassium, and base cations such as calcium and magnesium from the land to the sea) is of central importance. Such cycling of water and matter must be sufficiently frequent so as to provide the daily needs for all living organisms, including ourselves. At all levels of natural systems from an individual organism to an ecosystem, an exchange between the internal metabolism and the surrounding environment can be distinguished (effectively, life continues by pumping 'entropy' to the environment). These natural systems are arranged in such a way that the metabolites of one organism (system) become potential resources for other organisms, thus forming cycles at the next level.

Intelligent, sustainable land management requires a dynamic management of land towards better closed cycles of both water and matter. For the task of building and nurturing sustainable communities we can learn valuable lessons from nature – through the study of ecosystems and ecology. We need to become ecologically literate which means understanding the principles of ecosystems organization and using those principles for creating sustainable human communities (Capra 1996). Only in this way would a time perspective be opened up for the social economic development of future generations; future society may then participate in the further development of nature, together with mankind, and thus prolong the usability of nature as the carrier of societies within ecosystems.

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The play rules of nature

One of the main features of nature is how it deals with the elimination of randomness. For example, the ripple marks along a sandy shoreline show sorting and ordering properties; this results from the energy-dissipative dynamics between solid and liquid and/or solid and gaseous phases. The resulting structures are usually stable for much longer periods than an individual component (e.g. a sand grain) of the structure. Life seems to have evolved as the optimal strategy (maximum energy-dissipation, damping the motion of moving objects) to deal with such dynamics. Energy-dissipative structures sensu Prigogine (Prigogine 1980, Prigogine and Stengers 1984) are therefore the key to understand life processes, organisms and ecosystems.

All living organisms, although they are 'closed systems' in organisational terms, are 'open systems' with respect to continual flows of energy and matter. However, at higher organisational levels – such as an ecosystem – matter is continually recycled within the system while energy is dissipated. This means that ecosystems are, to a great extent (though not completely), closed systems with respect to the flow of matter, while energy is dissipated so as to achieve smooth temperature gradients, i.e. to provide ideal conditions for high biodiversity. Thus we can understand ecosystems as dissipative structures.

Energy dissipative units and the control of water and matter cycles. The smallest functional unit capable of mutual coupling to form internalized matter and water cycles while dissipating energy has been termed the dissipative ecological unit (Ripl and Hildmann 2000). Such ecological dissipative units steadily improve ecological resource efficiency by increasingly 'closing up' cycles. For a typical agroecosystem the dissipative ecological unit consists of five functionally-defined components which are:

(1) green plants, with the double function of (a) providing all heterotrophic organisms with energy in the form of organic matter, and (b) pumping water from the soil to the leaves, and by the way of evapotranspiration controlling moisture conditions and redox processes, e.g. access to oxygen in the soil and hence plant growth;

(2) dead organic matter – debris and/or humified debris – produced by all kinds of organisms, thus contributing to the abiotic parts of the soil, while the biotic component of the soils consists mainly of;

(3) bacteria and fungi as decomposers of organic matter and soil humic substances (debris);

(4) consumers including all kinds of animals. While the lower animals usually live in the soil on bacteria and fungi assembling the heterotrophic food-chain, the higher animals, such as mobile mammals, fish and birds, live either on other animals or on fresh green plant biomass. The consumers thus increase the efficiency of the dissipative unit structure by opening up space for organisms and their renewal. And, last but not least;

(5) water, as the most important dissipative transport-, reaction- and cooling medium. Water has three different dissipative properties: (a) to form the physical cycle between water and water vapor, (b) chemical reactivity by dissociation and controlling reactions, and (c) disintegrating the water molecule within living cells to form hydrogen and oxygen.

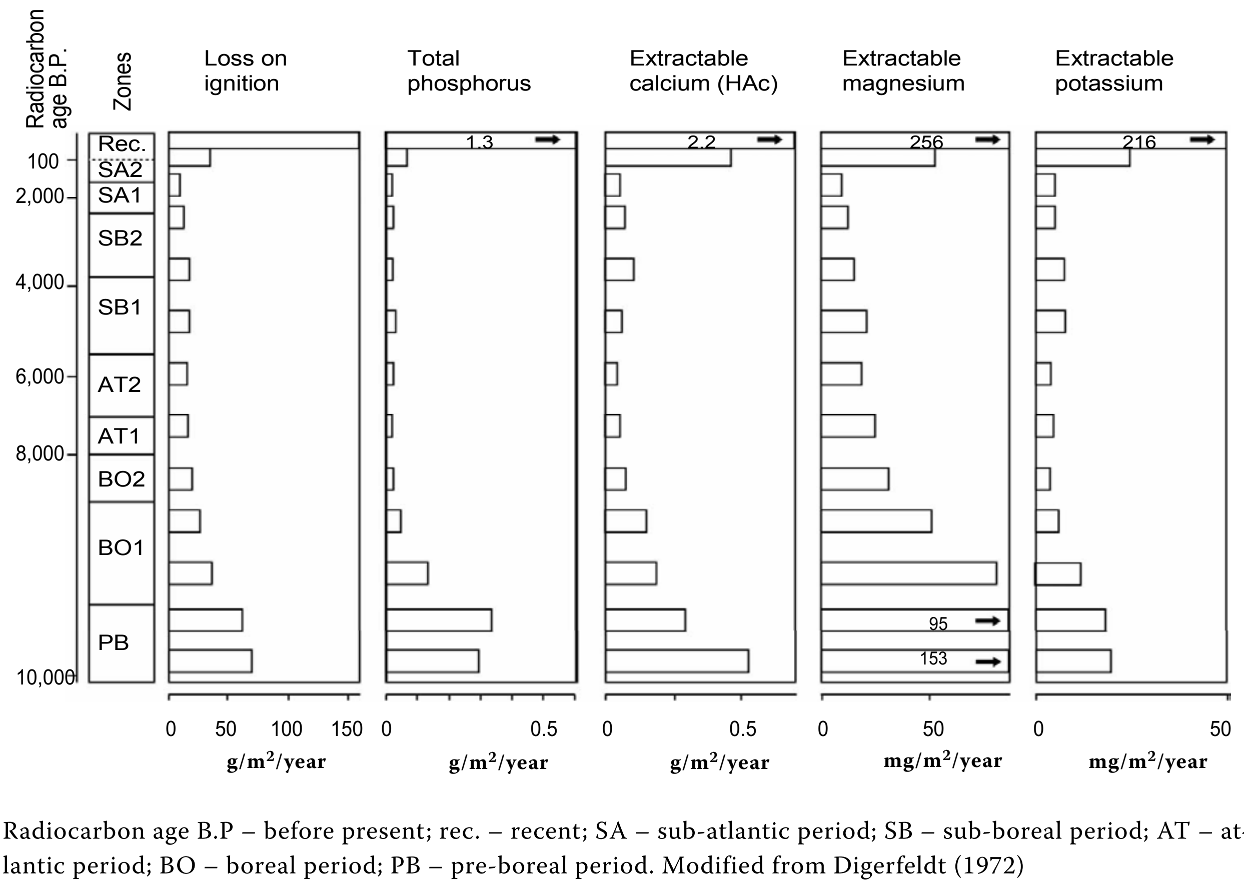
This dissipative assemblage of organisms together with the two abiotic components – organic matter and water – constitute the basic 'hardware' ('printed circuits') of ecosystems in the second phase of vegetation cover development – the climax coenosis (see below). At that point only assemblages of organisms capable of forming matter cycles low in losses are able to thrive improving the resource economy towards sustainable conditions.

Changes in vegetation cover and its impact on water and matter cycles and solar energy dissipation. The role of vegetation cover in regulating matter flows in river catchments can be traced and ultimately understood through an evaluation of the sedimentation rates in north European lakes during the different phases of vegetation development since the last glaciation retreated some 12 000 years ago. The recolonisation process of the barren denuded landscape, starting with colonies of pioneer plants but ultimately leading to climax vegetation, can be seen as a period of initially high losses – from catchments to lakes where the matter was deposited – but which gradually diminished (Digerfeldt 1972). During this establishment phase of plant cover lasting some 2000 to 3000 years and building up to that of a 'climax' ecosystem, almost all material losses decreased by roughly 90% to a minimum of matter flow – about one tenth of the original loss rates. However, when mankind started to interfere extensively with the vegetation cover some 200 years ago, matter losses increased by between 50 to 100 times that of the naturally-optimized amount (Figure 1). The destruction of natural vegetation cover over large areas has led to the opening of local water and matter cycles and to severe losses of material resources (i.e. nutrients and base cations) successively from the land to the sea. These losses are irreversible in the sense that the raising and disappearing of continents from and to the sea has a cyclic period of the order of some 200 millions years.

The above evidence describes how the destruction of natural vegetation cover has opened up water and matter cycles and resulted in accelerated, irreversible losses of matter – and consequently reduced soil fertility. Local, 'short-circuited' or 'closed' cycles of water have largely disappeared as natural vegetation has been increasingly cut down. The extensive drainage systems introduced to substantial land areas (both agricultural and urban) have further contributed to these losses. As the water content in the upper soil layer is lowered, more oxygen enters the soil and this in turn leads to increased oxidative processes and hence accelerates the mineralization of soil organic matter. Schlesinger (1997) observed that 20 to 30% of the soil organic matter was lost in soils brought under cultivation within the first few decades. A lowered content of soil organic matter lowers the soil water-retention capacity, hence leading to frequent water shortages in soils locally; equally, as the water retention throughout whole catchments has declined and myriads of short-circuited water cycles have disappeared, floods occur more frequently – there is little to slow down rain events from rapidly reaching river channels. By contrast, within a catchment area with well-established vegetation cover and consequently soil organic matter water can cycle over shorter distances – meaning that water evapotranspiration and condensation processes are completed within local cycles and over a short time-span. Such water, in the form of dew, is extremely important to maintain optimum micro- and meso-climatic conditions for vegetation stands. Equally important is that matter, more usually being transported with water flow, is now staying in place due to the water being cycled in short-circuited cycles.

Following on from this, it is clear how water and matter cycles are interconnected and, furthermore, why the disappearance of short water and matter cycles greatly hinders vegetation growth. But lack of water also disrupts a site cooling capacity, leading to much greater temperature amplitudes between day and night and between seasons. Thanks to water high heat capacity, it is the water cycle that plays such a crucial role in moderating temperature amplitudes. In landscapes with a low water table, for example a drained wheat field, a large proportion (60–70%) of incoming solar radiation is transformed into direct (sensible) heat – resulting

Figure 1. The post-glacial development of Lake Trummen – annual deposition



Radiocarbon age B.P – before present; rec. – recent; SA – sub-atlantic period; SB – sub-boreal period; AT – atlantic period; BO – boreal period; PB – pre-boreal period. Modified from Digerfeldt (1972) in elevated soil temperatures and hence increasing the mineralization rate of organic matter. In landscapes with abundant water resources, such as wetlands and forests, up to 80% of incoming solar energy can be bound as latent heat in water vapor and this energy is later released at the site of water condensation (Kravčík et al. 2008). The energy of solar radiation trapped in water vapor as latent heat is then transported to cooler sites where the vapor is released during water condensation as clouds and precipitation. The water cycle thus plays a very important role in energy dissipation throughout ecosystems.

In a landscape with sparse heat sinks – where cooler sites, such as forests and wetlands, are few and far between – evaporated water must travel over long distances in order to condense, say, above the sea or a mountain range. Such landscapes, with 'open' ('long') water cycles, are more prone to prolonged droughts and extreme floods, because dew and small rain events are scarce; rain usually arrives along with main weather fronts and the rain water quickly leaves the land due to the landscape low water-retention capacity – and, furthermore, taking with it the readily-soluble mineralized ions from overheated soils.

Where and when did agricultural practices lose sustainability?

We can trace the successively increasing inefficiencies in agricultural management back to the period of early industrialization and urbanization some 150 years ago. Since then agriculture itself has become increasingly industrialized, crop production largely separated from husbandry production, and the use of manure largely replaced by the use of artificial fertilizers. The food processing nowadays takes place often hundreds of kilometers away from the production site.

Rural populations have been successively deprived of their local markets as publicly-financed road construction has effectively heavily subsidized cities and industrial facilities and allowed them to grow. Localized production of daily requirements, especially with respect to water and energy, has been overhauled by all-consuming industrial structures within cities. Local renewable energy use, based on wood and charcoal, has been replaced by centralized non-renewable energy resources using coal and petroleum. The vast consumption of energy during two World Wars, and the destruction of industrial and social structures that they left behind, greatly accelerated the shift from sustainable to more and more resource-demanding practices and structures. All this have resulted in the loss of the original farming structure and the ability to recycle matter and to control, in part, water and climate conditions at production sites.

As compensation, society offered to deprived farmers a fig leaf – agricultural subsidies. Instead, the irreplaceable role of farmers in maintaining environmental quality and landscape sustainability should be widely recognized and adequately awarded.

Crop monocultures are responsible for high matter losses. In present-day farming systems, crop monocultures resemble much the same situation with regard to matter losses as pioneer plants that occurred after the last glaciation (Figure 1); the matter losses remain high as the assemblages of organisms that had developed throughout the centuries to form highly-efficient closed matter and water cycles have been replaced by far simpler organism assemblages that are continually being disturbed and thus unable to develop efficient feedback loops. Recent matter losses as high as 900 to 1500 kg/ha/year of dissolved solid matter, excluding NaCl, were observed in a predominantly agricultural catchment; the loss of base cations such as calcium reached 263 kg Ca/ha/year (Ripl and Hildmann 2003). With such high losses there is a continuous diminishing of base cations in topsoils as this can hardly be compensated for by the input of calcium by fertilizers (more than 650 kg/ha of calcium carbonate would have to be given back every year) or through rock weathering.

While being essential for the growth of plant tissue, base cations also serve as a buffer against the acidification of a site caused by the net productivity of plants as well as by the acids released during the mineralization of dead organic matter (Ripl and Hildmann 2000). The mineralization of organic matter speeds up under the water-unsaturated soil conditions. Hence the drainage of farmland has contributed to the loss of organic matter, the enhanced release of strong acids such as sulphuric and nitric acids and the further leaching of base cations. In the absence of base cations soil pH is lowered, and heavy metals become more mobile and thus of greater toxicity.

Compared to the losses of the base cations, losses of nutrients, such as nitrogen and phosphorus, are considerably lower; average losses of nitrogen from agricultural catchments are around 20–30 kg/ha/year (data review in Petersen et al. 1992, Ripl et al. 1995) and less than 1 kg/ha/year of phosphorus (Ripl et al. 1995, Mander et al. 1998). Nevertheless, even these seemingly unimportant losses are responsible for marked increases in the content of nitrates and phosphates in surface and ground waters.

Reduced soil fertility as a result of hazardous groundwater table management. Water flow and material losses generally determine the sustainability of agricultural land management. Soil management, vegetation cover and the flow dynamics of soil capillaries determine the proportion of water that is evaporated (and thus unconnected with material losses) and that which is recharging the groundwater (and leading to irreversible losses of matter). Surface flow of water (also carrying material losses) occurs when neither evaporation nor infiltration of water is possible and the retention capacity of the soil is exceeded.

Within the unsaturated soil zones usually during summer – these periods are being increasingly irregular and of greater amplitude (Ripl et al. 1995) – decomposition of organic matter proceeds whereby salts of nitric and sulphuric acids build up in the soils. Subsequently, when water tables in autumn and winter generally rise, these salts (mainly calcium and magnesium salts) are flushed out to the rivers that carry the matter losses to the sea. As measurements have shown, the leaching of base cations from agricultural soils caused by excessive decomposition of soil organic matter is some 50 to 100 times higher compared to unmanaged land in, for example, a virgin forest (Ripl et al. 2004). Estimations based on available concentration and flow data showed that in Germany the areal matter losses are on average between 1 and 1.5 tons of dissolved matter per ha per year (Figure 2), thus substantially reducing the soil fertility. The excessive decomposition of organic matter in aerated soils during summer is one of the major sources of carbon dioxide in the atmosphere and responsible for the imbalance in production/respiration processes (P/R < 1) indicating excessive soil respiration (see e.g. Schlesinger 1997).

Another matter of concern seems to be the increasing field sizes used for crop production. The removal of many field margins has further reduced the water retention capacities of soils and removed the cooling function of evaporating trees in farming landscapes. Vast areas readily becoming overheated during increasingly hot summer days cause the emissions from fields of fine particles containing most of the toxic compounds present there; the deposition of these compounds such as heavy metals in better-cooled wetland sites even damaging these 'islands' of potential sustainability.

Analysis of sustainable local land management

Prevention is better than cure. The prevention of water shortages is far better and a more sensible approach than trying to cope with droughts by introducing water-stress-tolerant crops; such crops would only aggravate the problem of water shortages and droughts further and for future generations. From the above, we can conclude that sustainable land management must focus on protecting and maintaining interlinked processes, and closing water and matter cycles – and thus leading towards localized organism assemblages with high biodiversity.

The main approach to sustainable land management will be to harmonize local processes. These

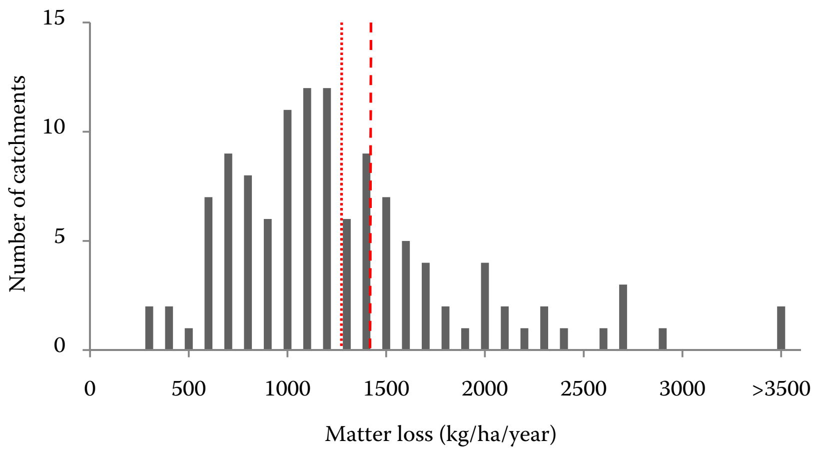


Figure 2. Total losses of dissolved matter (without NaCl) from catchments in Germany (dotted line = mean: 1283 kg/ha/year; dashed line = area weighted mean: 1426 kg/ha/year; number of catchments *n* = 121). Redrawn after Hildmann (2003)

processes usually occur where different structures 'meet' – at interfaces, where oxidative and reductive processes are located close to each other and least transport for reactants to close the process cycles is required. As a consequence, this helps build up a stabilized interface to the atmosphere and climate – the very 'backbone' of living systems. Resulting from the dynamic self-organization process of nature are small gradients of temperature and moisture as a prerequisite for biotope and species diversity. A good example of an optimized, self-organized system is a virgin forest where emissions, depositions and the concentration of protons are controlled by short-circuited water cycles. The pH is maintained at least one unit higher than the calculated mean pH of landscape precipitation with a ten-fold increase of water cycling in the atmosphere above the site. Above the virgin forest, water vapor rises only slightly higher than the forest crown, then returns daily as dew (Ripl et al. 2004). The short water cycle is as short as one day or less, consisting of dew production each morning and daily evaporation – the best possible pre-requisite for lower temperature fluctuations and more even precipitation events. In such a virgin forest, the debris layer is about three times thicker than that of managed forests and water-holding capacity is greatly increased by the fact that when trees fall they uproot a hole and create a little pond, which is successively filled in with leaf and needle debris and that provides, even under drought conditions, at least one to two millimetres of daily dew.

To ensure a sustainable future with our land management, we need to increase both natural vegetation cover and water-saturated soils within our landscape. As the upper parts of catchments are usually the most sensitive to the leaching and erosion of soils, these should be covered by unmanaged forest without net production. More wetlands are needed in the headwaters of our rivers to ensure more even flow rates and reduce flood risks further downstream. Riparian zones along streams and other wetlands naturally occurring in the depressions or littoral zones around lakes and ponds function as traps for matter losses thus preventing water eutrophication and pollution. All in all, more areas with water-saturated soils and natural vegetation are needed to enhance evapotranspiration as well as water retention in the landscape, i.e. to renew short-circuited water cycles. Agroforestry might be one possible solution for providing the necessary daily dew and lower the temperature amplitudes between day and night. Although these kinds of improved agricultural practices are slowly growing acceptance worldwide, the majority of agricultural areas continue to be ruled by more and more adverse regulations far away from any positive feedback processes.

By adopting optimized vegetation patterns in an intelligent land management approach, it should be possible to achieve the high functionality of natural processes and optimized agricultural and forestry production. A proper water and matter management would recycle all kinds of matter: including treated wastewater and sludge. On the one hand, this would increase soil fertility and on the other hand, enable the combined production of mixed types of food from plants and animals with short generation cycles, such as birds, fish and pigs.

The required strategic change

If sustainability of food production is the aim of society, then land management has to be radically changed. All subsistence products which can be harvested only from the land should be integrated in land management and closed water and matter cycles and soil fertility maintained over the important parts of the landscape. These goals are exactly the same ones that nature strives for when limitations and boundaries become discernible.

Based on our understanding of ecosystems as self-organized networks and dissipative structures, we can formulate some basic principles for sustainable human communities. All subsistence produce should be internalized within local communities, instead of supporting global food, energy and water markets. Instead of ever-growing production and ever-growing markets, life quality needs to be measured in terms of the quality of human interactions and communication, and the 'growth-economy' replaced by the 'steady-state economy' (a term originating from ecological economics) with its three main concerns which are sustainability, equity, and efficiency.

Regulations and laws which are centrally devised and applied universally are incapable of keeping in step with the functions of nature. Most of nature functions are only to be controlled by managing the soil system in direct feedback loops according to the soil conditions and resource distributions in time and space. Society should reward land managers for the integrated and sustainable production of all subsistence products like water, energy, food, climate, atmosphere and soil fertility together. As justified above, sustainable production in a long-term requires that short water and matter cycles are maintained which should be rewarded according to the evenness of temperature damping during the day and night and the minimalization of matter losses from land to the rivers and sea.

It is the small farming villages that will succeed urban industrial structures and help re-green countries. They will be the nuclei of development. At present, less than 3% of the population area manages about 86% of total land area (data for Germany; similar numbers apply for most of Europe) and this according to centrally-planned economic control through subsidies. Instead, farmers should be made responsible for sustainable land management where food production, water conservation and matter recycling are interconnected. By respecting natural processes and by incorporating recycling into all activities, instead of producing unusable wastes, human beings will again become part of nature.

In order to produce a sustainable future for our next generations, probably the most urgent tasks are the reduction of our need for ever-growing transport and logistics. If we continue as we are, with global transportation facilities remaining the prerequisite of our civilization prosperity, then the limited non-renewable energy resources will cause a dramatic cessation of our global common future.

Much technical innovation will need to be used to close the local cycles. It should be used proactively to stabilize the necessary dynamics of nature functions rather than the current efforts to defend structures and objects with growing deserts everywhere. A science which only explores the causalities between objects has to be overhauled to one which will evaluate and research the interaction patterns and their distribution in time and space – the future basis of the science of metabolism in the sense of Lovelock's 'Gaia hypothesis' (Lovelock 1990).

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