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Evapotranspiration – A Driving Force in Landscape Sustainability

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1. Introduction

It is clear from the ever-growing evidence that human interference with vegetation cover and water flows have considerably impacted water circulation in the landscape and resulted in major changes in temperature distribution. Human changes in land use – extensive river channelization, forest clearance and land drainage – have greatly altered patterns of evapotranspiration over the landscape. To comprehend how the changes in evapotranspiration impact landscape sustainability it is necessary to take a holistic view of landscape functioning and gain understanding of the underlying natural processes.

The Earth's surface has been shaped by water - in interaction with geological processes - for billions of years. Water and the water cycle - along with living organisms - have been instrumental in the development of the Earth's atmosphere; free oxygen in the atmosphere is the result of the activity of autotrophic, photosynthetic organisms (stromatolites) that evolved in seawater some 3.5 billions years ago. This was the beginning of aerobic metabolism and enabled the evolution of higher organisms, including higher plants.

The emergence of terrestrial plants some 400 million years ago has played a major role in the amelioration of the climate. The process of evapotranspiration – evaporation from surfaces and transpiration by plants - is instrumental in temperature and water distribution in time and space. Whilst evaporation is a passive process driven solely by solar energy input, transpiration involves an active movement of water through the body of plants - transferring water from the soil to the atmosphere. The process of transpiration is also driven by solar energy but plants have the ability to control the rate of transpiration through their stomata and have developed many adaptations to conserve water when water is scarce.

Water vapour is the main greenhouse gas playing a protective role against heat loss from the Earth's surface; on average the earth is about 33°C warmer than it otherwise would be without water vapour and the other greenhouse gases in the atmosphere (water vapour's

contribution being about 60 % on average, Schlesinger 1997). Water, thanks to its high heat-carrying capacity, is able to redistribute much of the solar heat energy received by the Earth through the water cycle: by evapotranspiration and condensation. Water evapotranspiration and condensation therefore plays an instrumental role in climate control with regard to temperature distribution in time and space, i.e. reducing the peaks and modulating the amplitudes of high and low temperatures on the land surface - making conditions on Earth suitable for life.

The natural vegetation cover that has developed over the Earth throughout millennia is best suited to utilize and dissipate the incoming solar energy, and to use the available water and matter in the most energy-efficient way. There is ample evidence for this. Since the time that human civilization begun greatly interfering with the landscape's natural vegetation cover - clearing forests, ploughing savannas and draining wetlands for agricultural use and urban settlements - many environmental problems have started to appear. More recently environmentally sustainable management systems have been sought - with various degrees of effort and understanding of the underlying problems.

In this chapter we will provide evidence of the role of water and vegetation in shaping the climate. Using data and observations from a virgin forest in Austria we will present and discuss the play rules of nature and offer a definition of landscape sustainability. We will present a living example of reduced precipitation over an area of 4000 square kilometres following the partial clearance of the Mau Forest in western Kenya and describe the situation in the de-watered landscape of the open-cast mining area of North-West Bohemia, Czech Republic. The connection between the disturbed water cycle and matter losses in the predominantly-agricultural Stör River catchment in Germany will be demonstrated and the role of evapotranspiration in maintaining landscape sustainability discussed.

2. The play rules of nature in search of sustainability

2.1 The energy-dissipative properties of water

Life on Earth depends on energy, water and a few basic elements (mainly C, H, O, N, P, S and about 20 others) that constitute living tissue. The biogeochemical cycles - the continuous cycles of matter and water - are essential for life to be sustained. The cycles are primarily powered by the energy received from the Sun. Driven by the sun's radiation water is cycled continuously: playing an instrumental role in energy dissipation and the cycling of matter. The dissipation of solar energy at the Earth's surface - i.e. the distribution of energy in time and space - creates suitable thermal conditions for natural processes and life on Earth.

To understand how the natural processes involved in energy dissipation are inter-related Ripl (1992, 1995) proposed a conceptual model based on the energy dissipative properties of water. In his Energy-Transport-Reaction Model (ETR Model), Ripl considered three essential processes (Fig. 1) that control the dissipation of energy:

- the process of water evaporation and condensation;
- the process of dissolution and precipitation of salts; and
- the process of disintegration and recombination of the water molecule within the biological cell

With water's high capacity for carrying energy in the form of latent heat, most energy is dissipated by the physical processor property of evaporation and condensation, making water a very efficient cooler or heater. When water changes from a liquid to its gaseous phase - as in evapotranspiration - energy is stored in the water vapour in the form of latent

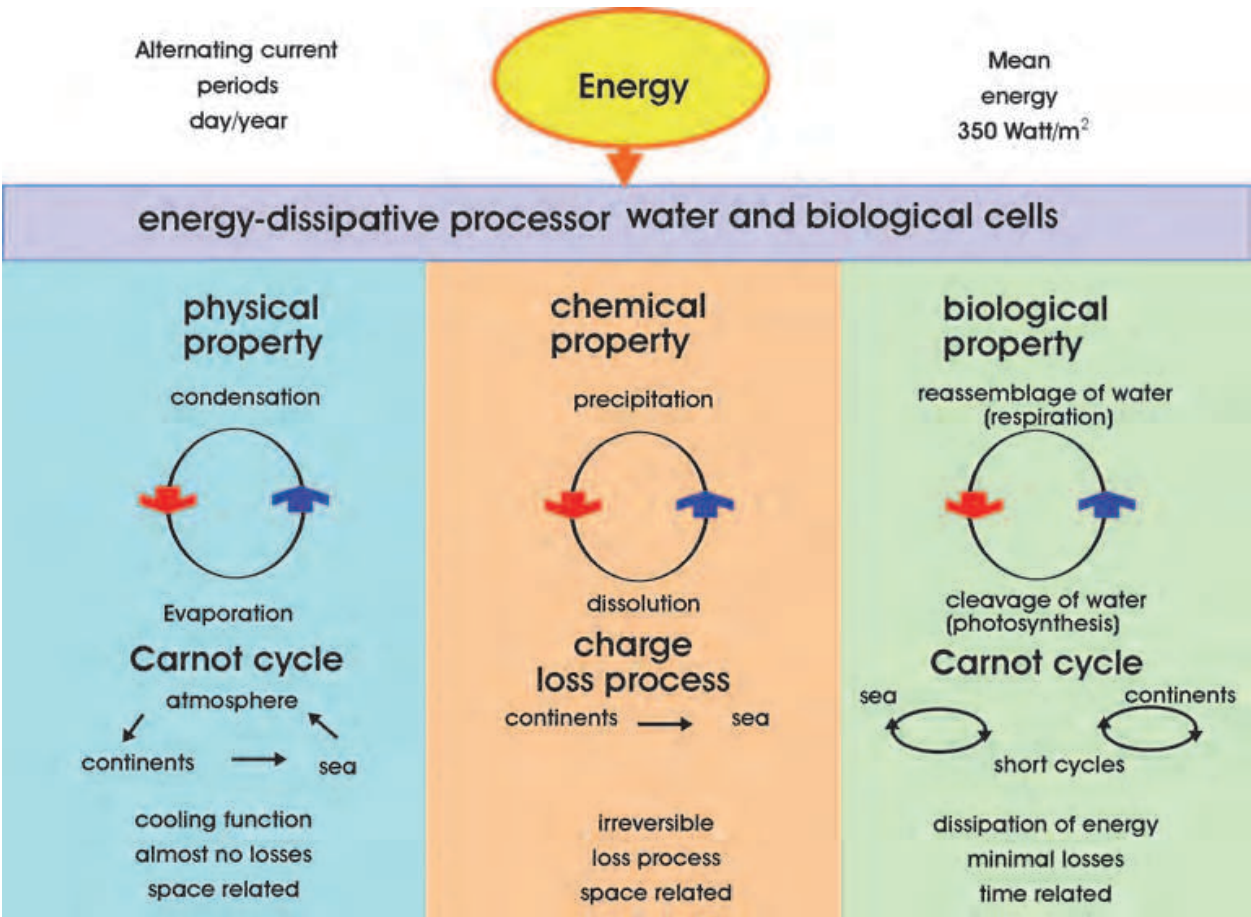


Fig. 1. Three processor properties of water

heat and the local area is cooled down. At night or early morning when water condenses on cooler surfaces, energy in the form of latent heat is released and the local area is warmed up. Without water, the energy of the incoming radiation is transformed into sensible heat and the local area becomes overheated during the day and likewise far cooler at night (as is well known from desert areas, with differences between day and night temperatures typically exceeding 50°C). Water-saturated landscapes provide much more stable environments than do dry terrestrial systems. In landscapes with water - abundant aquatic ecosystems, wetlands and soils with high water retention capacity - about 80 % of incoming solar energy is stored as latent heat of water vapour via evapotranspiration, whilst in de-watered landscapes (with a low-water retention capacity) the vast majority of solar energy is transformed into sensible heat (Pokorný et al. 2010b). In exceptional cases when, for example, hot air of low relative humidity moves across a wetland surrounded by dry areas, even more than equivalent of 100% of solar radiation can be stored safely in latent heat (Monteith 1975, Ryszkowski & Kedziora 1987, Kučerová et al. 2001). Below in Sections 3 and 4 we will show the high temperature differences measured between de-watered areas and sites with a good supply of water and high evapotranspiration.

Water has another important natural property - the ability to separate the charges in a given amount of molecules into protons and electrons. This chemical processor property of water is responsible for the dissolution of salts - using up the water's heat energy in the formation of ionic solutions - and then if concentrated by subsequent evaporation of the water crystals

can be precipitated from the solute, releasing the same amount of energy as was required by the dissolution process. However, through dissolution and precipitation a much smaller fraction of energy is dissipated compared to evaporation and condensation.

In pure distilled water at 20°C, 10^{-7} moles of water are dissociated into protons (H^+) and electron-charged hydroxyl ions (OH^-). These electric charges represent chemical potentials, i.e. energy with the potential to be converted into chemical reactions. The number of charged parts (ions) per volume of water constitutes the concept of reactivity (pH, law of mass action). Importantly, reactivity is to a large part dependent on the temperature-, concentration- and pH gradients existing at various interfaces. Such interfaces between solid, liquid and gaseous phases are of special interest in all energy processes and provide sites for steady rates of change. Being essential tools for life processes, nature produces membranes and surfaces where life's important reactions can most readily take place. Even without there being differences in temperature at a liquid- (water-) solid interface, chemical reactions can still readily take place due to the singularity of charge distributions and the modulations of thermal motion (the thermal 'jiggling' of molecules / ions).

Kinetic energy ($mv^2/2$) consists of the frequency and amplitude of accelerated masses. At the interfaces between two phases (e.g. liquid-solid) a modulation of the mass movement of ions (molecules) can occur, especially in amplitude; reactivity is thus enhanced and reaction probabilities increased (in conditions of decreased pH and elevated proton density). As an example of this, take the distribution of highly-diluted, colloidal organic matter in a glass beaker of water. The organic colloids are coagulated at the glass wall, attracted and thus concentrated by the lowered pH conditions at the liquid-solid interface; this enables potential bacterial activity such as, for example, quicker growth of bacteria and decomposition of organic matter. Such phenomena are ubiquitous in nature: always occurring, for example, between the root membranes of plants and the interstitial water of the soil. Evapotranspiration by the leaves of plants lowers the water content in the capillary network of the soil interstitium, giving access to the oxygen of the air and thus exerting a positive feedback on root activity. If the 'water pump' of a productive growing plant should for some reason stop, then electron density (i.e. low redox conditions) will rise and decomposition processes will be severely retarded. Thus the activity of evapotranspiration – the switching on or off of the plant's water pump – controls soil bacterial activity and mineralization processes. In this way highly-efficient processes – control mechanisms closely connecting functioning plant systems and soil – are able to maintain loss-free conditions in the soil. Minerals and nutrients become 'available' only when the plant is actively growing and thus are readily 'used up'. The losses induced by the percolation of 'free' nutrients and minerals released by mineralization through to rivers via sub-surface groundwater flow are thus minimized. Such a mechanism is steadily optimizing the sustainable development of vegetation cover over the landscape by minimizing the irreversible losses from land sites to the sea (Ripl 2010).

Water is also the most important agent in the biological processes of production (photosynthesis) and decomposition (respiration) of organic matter. During photosynthesis water is split into reactive $2H$ and O . Oxygen is released to the atmosphere and hydrogen is used for the reduction of carbon dioxide to carbohydrates - organic compounds including sugars, starch and cellulose. The solar energy bound in organic matter is released again during mineralization (decomposition) when oxygen is used up to split sugars back into

CO₂ and H₂O. As the production and breakdown of organic matter generally occur within the same site, the biological process can be considered cyclic just like the physical dissipative process. However, considerably less incoming solar energy (about 1 - 2%) is bound by photosynthesis compared to that of water evaporation; the net efficiency of solar energy conversion into plant biomass is usually between 0.5 and a few percent of the incident radiation (for more details see, for example, Blankenship 2002).

The theories and ideas associated with dissipative structures, open dynamic systems operating far from equilibrium, and self-organization (Prigogine & Glansdorff 1971; Prigogine 1980; Prigogine & Stengers 1984) have given us a clearer understanding of how living organisms utilize a throughput of external energy to create new order and structures of increased complexity (Capra 1996). These theories cast light on how ecosystems have organized themselves during evolution: maximizing their sustainability through cycling water and matter and dissipating energy. The dissipation of energy takes place at various scales - from the micro-scale within cells to ecosystems and landscapes (Schneider & Sagan 2005). At the landscape level, evapotranspiration plays an essential role in energy dissipation and as such is highly dependent on the vegetation cover and water availability.

2.2 Plants and water availability

Water is supplied to the land and its vegetation through precipitation. The various sources of water contributing to precipitation differ in different regions of the Earth. In maritime regions, water derived from evaporation from the sea prevails whilst further inland precipitation may be derived equally from long-distance atmospheric transport of water from the sea and from evapotranspiration from within the basin itself (Schlesinger 1997). Availability of water is one of the most important factors determining the growth of plants: hence the distribution of plants on Earth coincides with the availability of water. Deserts are typically short of water and thus the vegetation is rather scarce or non-existent. Nevertheless, plants have developed a number of different strategies during evolution to cope with both conditions of water abundance on the one hand and water scarcity on the other. For the purpose of this chapter we will focus on mechanisms that plants use to control the local water cycle and why it is important.

There are several mechanisms that plants use to control the loss of water from their tissues. One of these is the operation of stomata, their intricate structure, position on plants, their size and numbers. Stomata are found in the leaf and stem epidermis of plants; they facilitate gas exchange and the passage of water from the leaf or stem tissues to the surrounding air by controlling the rate of transpiration. Stomata consist of a pair of guard cells, the opening between them providing the connection between the external air and the system of intercellular spaces. Plants adapted to dry conditions mostly have small stomata immersed within the epidermis. Numbers of stomata differ from about 50 to 1000 stomata per mm². Stomata respond to the amount of water in the leaf tissue and to air humidity: closing when the water content in leaf tissue is low and when ambient air humidity declines. In such cases only a small amount of water is transpired through the cuticle (a wax layer on the epidermis). In plants with a thin cuticle - most wetland plants (hygrophytes) belong to this category - the cuticle transpiration may amount to a considerable percentage of total transpiration. However, cuticle transpiration usually amounts to only a few percent of the

water released by stomatal transpiration. The effectiveness of the cuticle in reducing loss of water is well seen in fruits, such as apples and pears, or potato tubers: if unpeeled they can stay many weeks without any great water loss (Harder et al. 1965).

Transpiration by plants can be seen as a water loss in such cases as water scarcity; managers of water reservoirs that supply drinking water would usually see it as a loss. For a plant, however, transpiration is a necessity by which a plant maintains its inner environment within the limit of optimal temperatures. And at the level of landscape, evapotranspiration is the most efficient air conditioning system developed by nature.

In addition to optimising temperature, through evapotranspiration plants control the optimum water balance in their root zone. The activity of plant roots in respect to water uptake regulates the redox conditions in the root zone, thus regulating the rate of organic matter decomposition that makes nutrients available for plants growth. It is therefore most likely that, through evapotranspiration, the vegetation cover controls the irreversible losses of matter: an efficient system where only so much organic matter is decomposed such that those mineral nutrients freed from organic bonds are rapidly taken up by plants for their nutrition.

In dry environments, plants have developed ways to attract water condensation. As water condensation takes place on surfaces, plants growing under the conditions of water-scarcity typically have a high surface-volume ratio. Spines and hairs on plants have developed to increase the plants' surface-volume ratio - thus providing more surfaces for water condensation (Fig. 2). Given the complex role of vegetation in maintaining a water balance, smooth temperature gradients and a control of matter cycles in the landscape, any potential economic profits expected from the destruction of natural vegetation cover need to be carefully weighed against the loss of the functioning role of vegetation.



Fig. 2. Spines and hairs on cacti enhance water condensation in arid environments (Photo: M. Marečková)

2.3 Water dynamics and matter losses

It is generally accepted that water is the most important transport and reaction medium – many chemical reactions can only take place in the presence of water and matter is transported mainly with water flow. Matter that is transported via rivers to the sea – both in a dissolved or particulate form – has to be seen as an irreversible matter loss for continents and their vegetation as it takes millions of years before the sea floor is lifted up to form a new continent. Equally, matter that is leached through the soil to the permanent groundwater is further unavailable for nutrition of the vegetation cover on land. Ripl (1992) used data from palaeolimnological studies of lake sediments in southern Sweden (Digerfeldt 1972) to demonstrate the role of vegetation cover in matter and water flows. Vegetation cover reconstruction and sediment dating has made it possible to document four distinctive stages in landscape and vegetation development in postglacial North European catchments and the relevant matter losses at each stage. During the first stage, the bare soils or soils with scarce pioneer vegetation that occurred after the retrieval of glaciers were prone to elevated soil erosion and high transport of dissolved matter. This was measured as a relatively high rate of matter deposition in lake sediments; analysis showed that sediment deposition rates were highly correlated with the deposition rates of base minerals, nutrients and organic material. When climax vegetation became established within catchments, rates of sediment deposition diminished some ten fold. With a fully developed vegetation cover in catchments, low deposition rates of approximately 0.1 to 0.2 mm per year remained rather constant right through until the second half of the 19th century. Since then increasing rates of sewage discharge to lakes, clearance of forest and intensification of agriculture have led to deposition rates increasing nearly a hundred fold to present levels of 8 to 10 mm per year.

The reduction in matter losses from catchments covered by climax vegetation is ascribed to the increased system efficiency of water and matter recycling. In catchments with a well-developed vegetation cover, water and matter are bound to short-circuited cycles and losses are minimal. In contrast, the increased clearance of forest, exposure of bare land, and drainage of agricultural land have accelerated matter losses from catchments. The lowering of the water table by humans has increased the rate of mineralization of organic matter and also enhanced water percolation through soils that carries away the dissolved mineral ions and nutrients. The increased inputs of nutrients to water bodies were documented by the much higher deposition rates of sediments – the beginning of eutrophication (Digerfeldt 1972, Björk 1988, Björk et al. 1972, 2010).

Ripl et al. (1995) confirmed by a laboratory lysimeter experiment that the water dynamics in a soil substrate has a major impact on the rate of organic matter decomposition; under the conditions of intermittent wet and dry phases more organic matter was mineralized and higher amounts of mineral ions leached through the soil than from the control soil substrate with a continuous water flow. The significance of interchanging dry/wet phases and its decisive role in matter losses can be documented also by many examples of drained lowland fens in northern Europe, where increased matter losses have been observed following fen drainage. The mineralization of organic matter accumulated throughout centuries has been of such dimensions that soil subsidence, for example in the fenland of Cambridgeshire, England, has amounted to more than 4.5 metres following the drainage that took place there in the 1650s (Purseglove 1989). By contrast, permanently moist soils slowly accumulate organic matter and matter losses are minimal.

2.4 Specific features of energy fluxes in wetland ecosystems – primary production and decomposition of organic matter

Wetlands which are eutrophic, i.e., well supplied with plant mineral nutrients, are highly productive because they do not suffer from water shortages. Individual types of wetlands differ significantly - not only in their production of plant biomass but also in their capability of long-term accumulation of dead organic matter (as detritus or peat). This capability depends on the ratio between average rates of primary production and decomposition. For example, bogs are distinguished by their low annual primary production of biomass (usually only 100 to 250 g m⁻² of dry mass). Nonetheless, the strongly suppressed decomposition of organic matter that is produced in bogs results in a net annual accumulation of dead plant biomass that is eventually transformed into peat. As the peat layer grows upwards, the bog vegetation loses contact with the groundwater rich in minerals and its biomass production slows down. In contrast, though eutrophic fishponds have a typical primary production one order of magnitude higher than in bogs, they often hardly accumulate any dead biomass as the annual decomposition approaches or equals annual net primary production. In fishponds, however, like in other wetlands, the production to decomposition ratio depends on the supply of nutrients (especially P and N), i.e., on the trophic status of the water (Pokorný et al. 2010b). Thus any lake or fishpond, if oversupplied with nutrients, can accumulate a nutrient-rich organic sediment if the decomposition rate cannot keep pace with the extremely high primary production. Eventually, the fishpond becomes a source of nutrients; when oxygen gets depleted and anaerobic conditions at the sediment-water interface occur, phosphorus is released from the sediment enhancing the primary production even further.

2.5 Landscape sustainability

2.5.1 The dissipative-ecological-unit

The Earth's atmosphere has been described by Lovelock (1990) as an open system, far from equilibrium, characterized by a constant flow of energy and matter. Equally, living organisms are open systems with respect to continual flows of energy and matter. However, at a higher organisational level – such as an ecosystem – matter is continually recycled, i.e., what is a waste for one organism becomes a resource for another. Ripl & Hildmann (2000) termed the smallest functional unit that is capable of forming internalized cycles of matter and water while dissipating energy - the *dissipative-ecological unit* (DEU). The steadily increasing resource stability of DEUs is achieved by their reduction of water percolation through soils to the groundwater and instead their increase in local, short-circuited water cycling within ecosystems by enhancing their evapotranspiration.

The concept of the dissipative-ecological-unit is used to demonstrate how nature, when not disturbed by sudden changes in climatic conditions, tends to close cycles of matter, i.e. run an efficient local resource economy and maintain relatively even temperatures and moisture conditions.

2.5.2 Evapotranspiration and landscape sustainability

Results from a detailed study conducted in a predominantly agricultural catchment of the River Stör in NW Germany demonstrated how the destruction of natural vegetation cover over large areas has led to the opening up of cycles due to the disturbance of natural water flow dynamics (Ripl et al. 1995, Ripl & Eiseltová 2010). Water and matter no longer cycle within localized, short-circuited cycles; instead, reduced evapotranspiration has resulted in

increased water percolation through the soil accompanied by increased losses of matter. The average losses of dissolved mineral ions measured within the Stör River catchment were alarmingly high, about 1,050 kg of mineral salts per ha and year (excluding NaCl). A detailed description of the measurements performed and methods used can be found in Ripl and Hildmann (2000). Such land management systems are unsustainable in the long-term as soil fertility will inevitably be gradually reduced.

A rather different situation can be observed in an undisturbed ecosystem, such as the rather unique virgin forest of Rothwald in Austria. Here the feedback control mechanism of this complex mature forest ecosystem is functioning according to the rules of nature. It is the interlinked vegetation cover that is in control of the processes. In this dolomitic bedrock area groundwater is very scarce - being present only in minor crevices. Oscillations of the water table within the thick debris layer are mainly controlled by the plants through their evapotranspiration. Despite the relatively high precipitation - over 1,000 mm a year - the run off from the virgin forest remains very low and is restricted mainly to the period of snow melt above frozen ground (February till May). The site does not suffer from shortage of water as can be deduced from the highly damped temperature distribution; the temperature amplitudes between day and night almost never exceed 8-9°C during summer (Ripl et al. 2004). The organic matter decomposition is rather slow due to the water-saturated conditions and the debris layer is rather high. The debris layer was 2-4 times higher in the Rothwald virgin forest than in the large areas of neighbouring managed forest (Splechtna, pers. comm., 2000). Water analyses of melted snow samples showed extremely low conductivity values (Table 1). This indicates that there is a much quicker turnover of water evaporated from the virgin forest in relation to precipitation brought from long distances away, as such precipitation water would have about 10 times higher conductivity. It is estimated that very short water cycles with a frequency of one day or less must be prevalent.

	Conductivity at 20° C mS m ⁻¹	Alkalinity mmol l ⁻¹	pH
Max	1.45	0.09	7.22
Min	0.26	0.00	4.73
Median	0.60	0.01	6.27
MW	0.72	0.03	6.49
no. of sites	17	16	16

Table 1. Conductivity, alkalinity and pH measured in melted snow from Rothwald virgin forest.

Based on the findings described above we can define landscape sustainability as the efficiency of the landscape to recycle water and matter, and to dissipate the incoming solar energy. We have provided evidence that matter losses increase with increased water percolation through soil - as a result of reduced evapotranspiration due to natural vegetation clearance. In the following sections we provide data from a thermal camera and satellite images. These data give supporting evidence that evapotranspiration plays a major role in the dissipation of the incoming solar energy and dampening temperature amplitudes.

3. Evapotranspiration as seen by thermal camera

Pictures of the landscape using a thermal camera show distinct differences in the temperatures of forest, grassland, bare soil and buildings. Even over relatively small areas of a few square metres, temperature differences can be over 20° C. Dry surfaces, such as concrete, when exposed to sunshine are the warmest, despite their higher albedo (higher reflection of solar radiation). This demonstrates that the surface temperatures in the landscape are controlled mainly by the process of water evapotranspiration while the albedo plays a less important role.

On a sunny day, dry surfaces such as the road show the highest temperature (up to 45° C), whilst meadows and forests have lower temperatures as they are cooled by evapotranspiration (Fig. 3). The cooling efficiency depends on water availability and vegetation type. The maize field (Fig. 4) shows a higher temperature over the bare soil (up to 47 °C) than on the top of the stand (32° C). Air heated by a warm soil ascends upwards and takes away water vapour. In hot air crops lose a high amount of water in the form of water vapour.

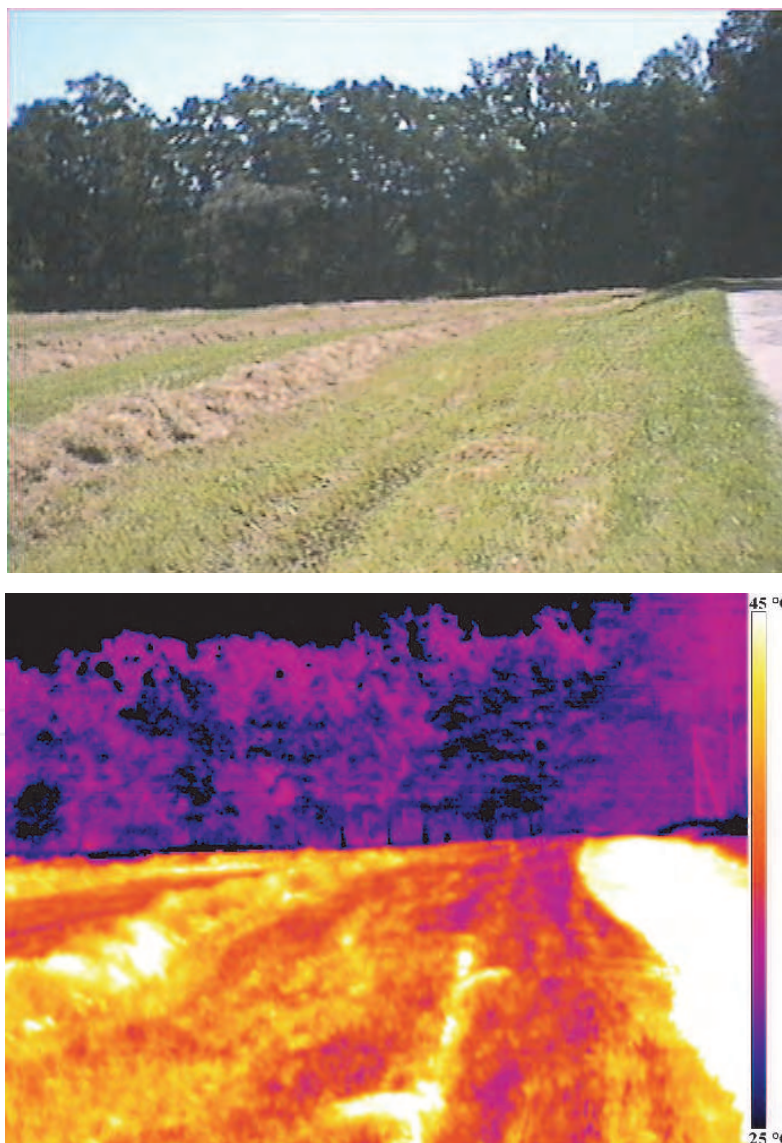


Fig. 3. Surface temperature of a drained meadow, road and forest as seen by thermovision camera on 17 July 2009 at 9.40 GMT+1 near the town of Třeboň, Czech Republic.

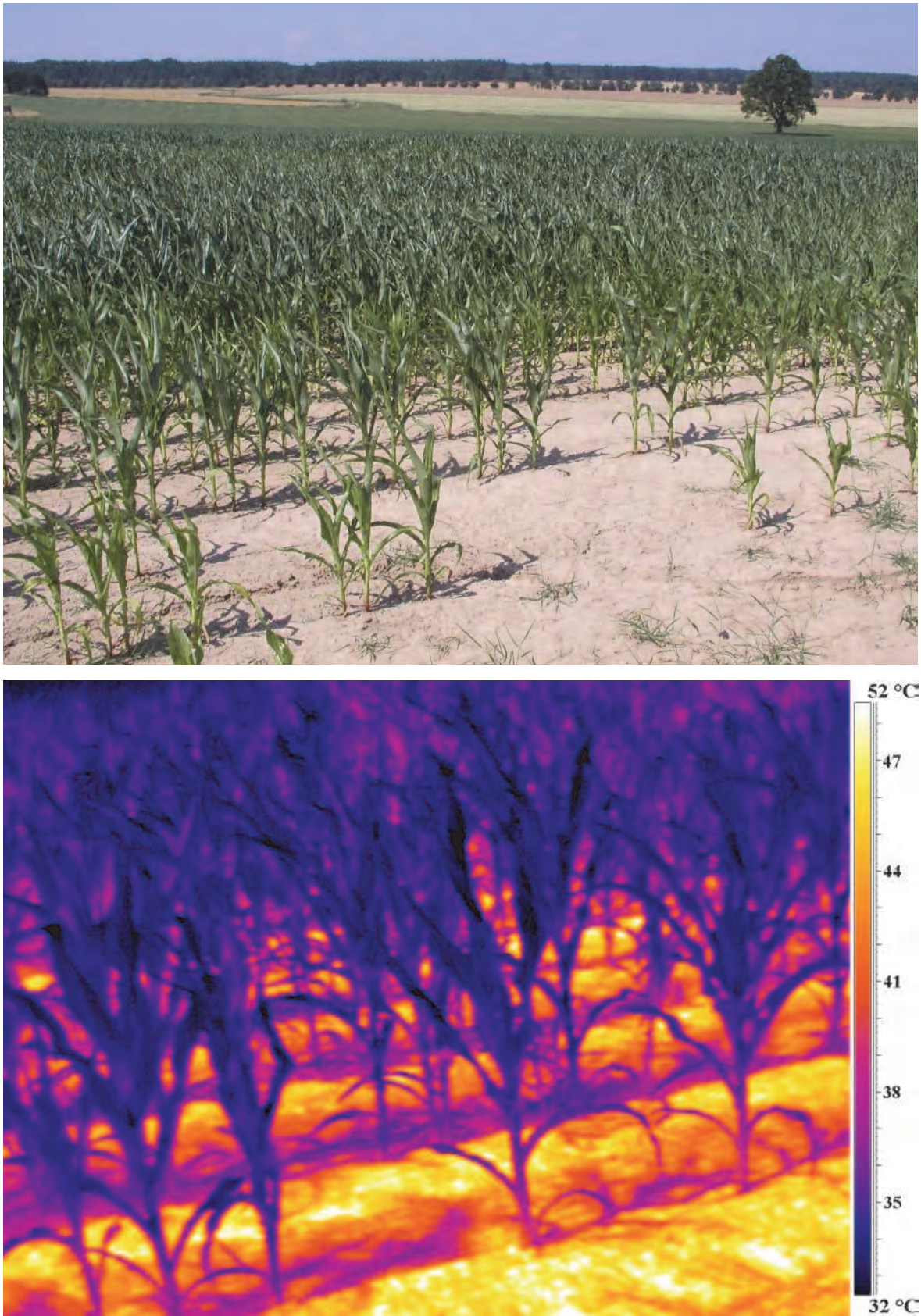


Fig. 4. Maize field and its surface temperature as seen by thermovision camera on 16 July 2010 at 14.19 GMT+1 in the vicinity of the town of Třeboň, Czech Republic.

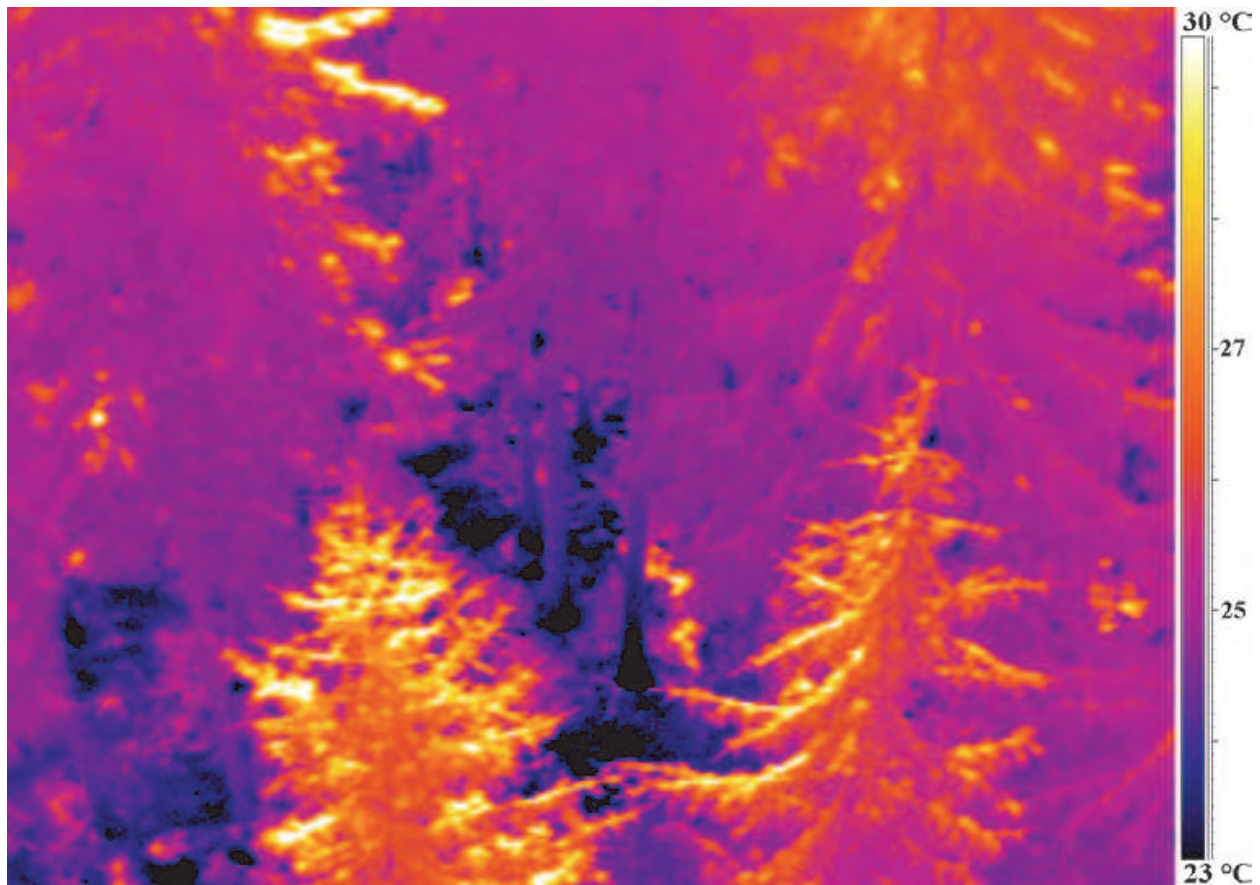


Fig. 5. Surface temperature of forest canopy as seen by thermovision camera on 13 July 2010 at 14.15 GMT+1 in Novohradské hory, Czech Republic.

The vertical distribution of temperature in a forest canopy is opposite to that observed in a maize field. During a sunny day in a forest, a temperature inversion – a lower temperature at ground level in the shrub layer (23 – 26° C) than on tree crowns in the forest canopy (29.5° C) - has been observed (Fig. 5). A heavier cold air stays at the ground and hence the water vapour may condense on herb and shrub vegetation even during a sunny day. When temperatures go down at night the air becomes more saturated and condensation occurs above the tree canopy. Makarieva and Gorshkov (2010) have shown that intensive condensation is associated with the high evaporation from natural forest cover that is able to maintain regions of low atmospheric pressure on land – i.e. forests constitute acceptor regions for water condensation and precipitation.

4. Use of satellite images to assess cooling efficiency of vegetation cover

Satellite remote sensing data from the Landsat thermal infrared channel provide a suitable tool to evaluate the spatial and temporal distribution of land surface temperatures. This can be used to assess and compare the cooling efficiency of different vegetation cover types or land use. Two model sites (in central Europe and eastern Africa) were selected to demonstrate the role that a functioning vegetation cover plays in energy dissipation compared to the situation of bare or sparsely vegetated land characterized by highly reduced evapotranspiration and shortage of available water.

4.1 North-west Bohemia

4.1.1 Site description and methods

Landsat multispectral satellite data were used to analyze the effects of different land cover types on surface temperature. Two scenes - from 1 July 1995 and 10 August 2004 - were used to compare, firstly, the long-time change in vegetation cover and its effect on temperature distribution, and, secondly, the effect of seasonality of farming land. The selected model area of North-West Bohemia, Czech Republic and Saxony, Germany covers 8,722 km² (102 x 85 km). The site was selected to include different landscape types with a heterogeneous mix of land use – highly intensive agriculture, industrial areas and an open-cast brown coal mining area, small-scale farming lands, and broad-leaf and coniferous forests. Supervised classification methods (Mather & Tso, 2009) were used to classify the land cover; five categories were defined – bare grounds, water, forest, non-forest vegetation and clouds. Surface radiation temperatures were calculated from the standard mono-window algorithm (Sobrino et al. 2004), using a conversion of thermal radiance values from the Landsat thermal infrared channel. As the satellite images selected differ in year and season, the temperature data were standardized by the normalization method of z-scores using the following equation:

$$Z = \frac{x_i - \bar{x}}{\sigma}$$

where x_i is the temperature value of a pixel, \bar{x} is the mean average temperature, and σ is standard deviation.

Date	Min. temperature ° C	Max. temperature ° C	Mean average temperature ° C	Standard deviation
1 July 1995	9.6	46	23.1	2.9
10 August 2004	12.3	46	24.1	4.8

Table 2. Temperature values calculated from Landsat thermal channel.

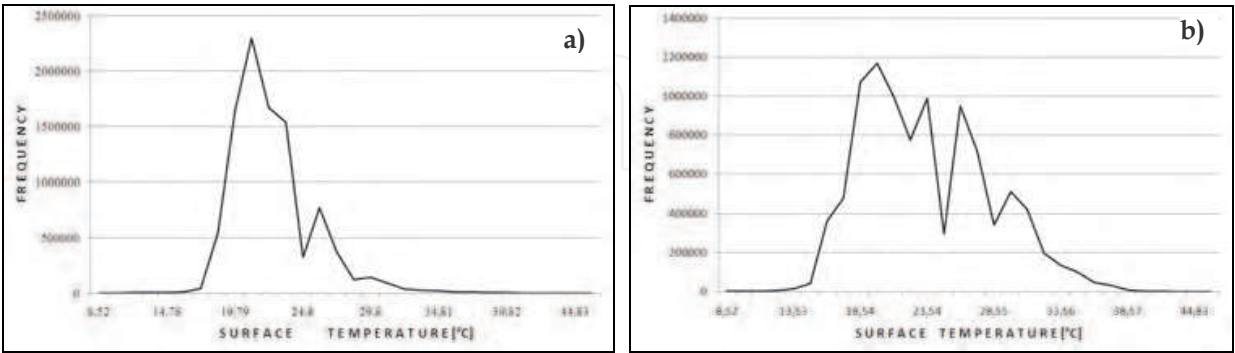


Fig. 6. Histograms showing frequencies of temperature distribution in satellite images of a) 1995 and b) 2004.

The result of normalization is a temperature image with a relative scale showing a range from minimum to maximum temperature. The real temperature values are given (Table 2) and their frequency of distribution displayed by histograms (Fig. 6).

4.1.2 Satellite data interpretation

The relationship between different land-cover types and their relative surface temperature distributions is shown in Figures 7 and 8. Surface temperature is an indicator of the system's

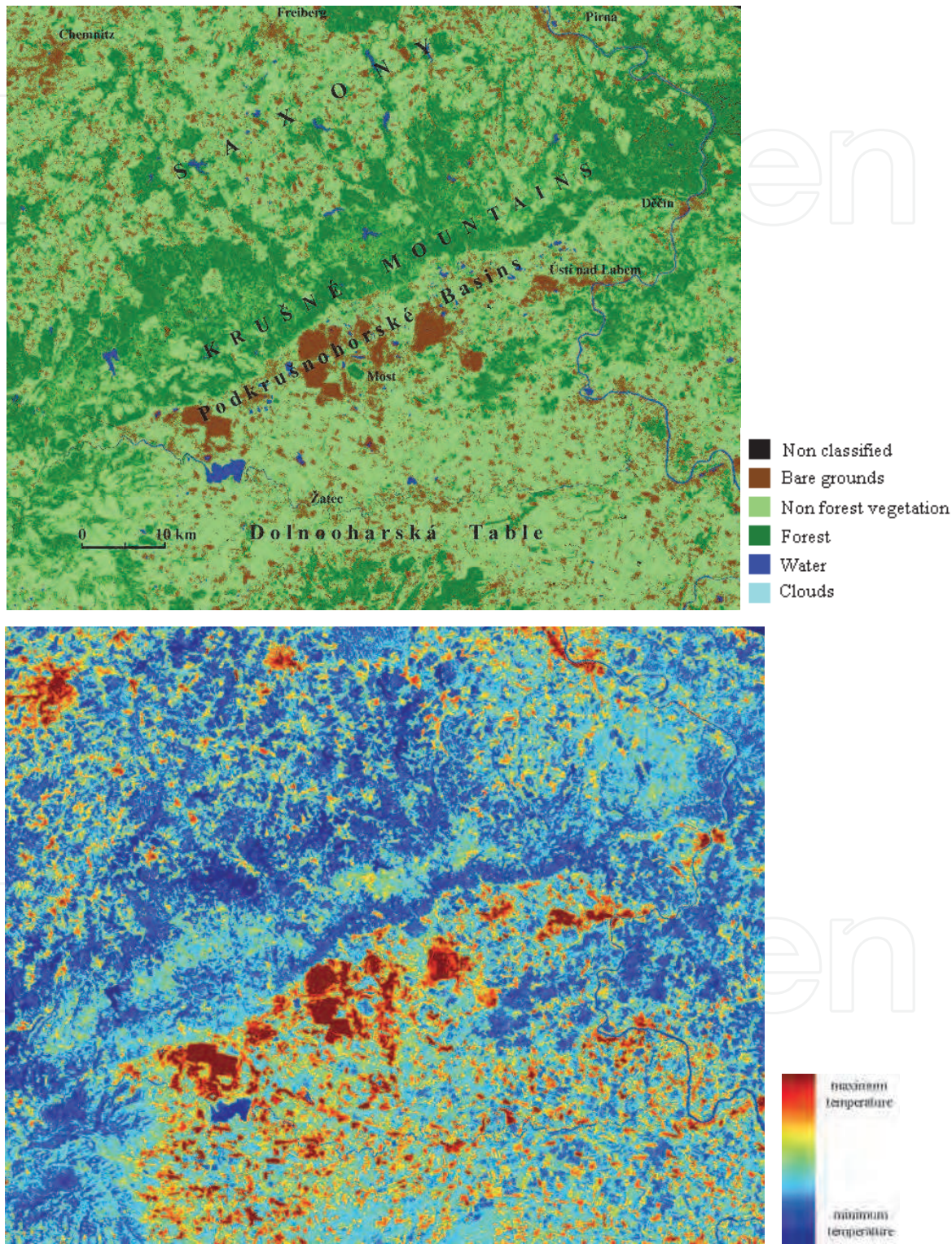


Fig. 7. Land cover (upper image) and temperature distribution (bottom image) over the model area of North-West Bohemia and Saxony obtained on 1 July 1995 at 9.40 GMT+1. The surface temperature data were obtained from Landsat thermal channel TM 6.

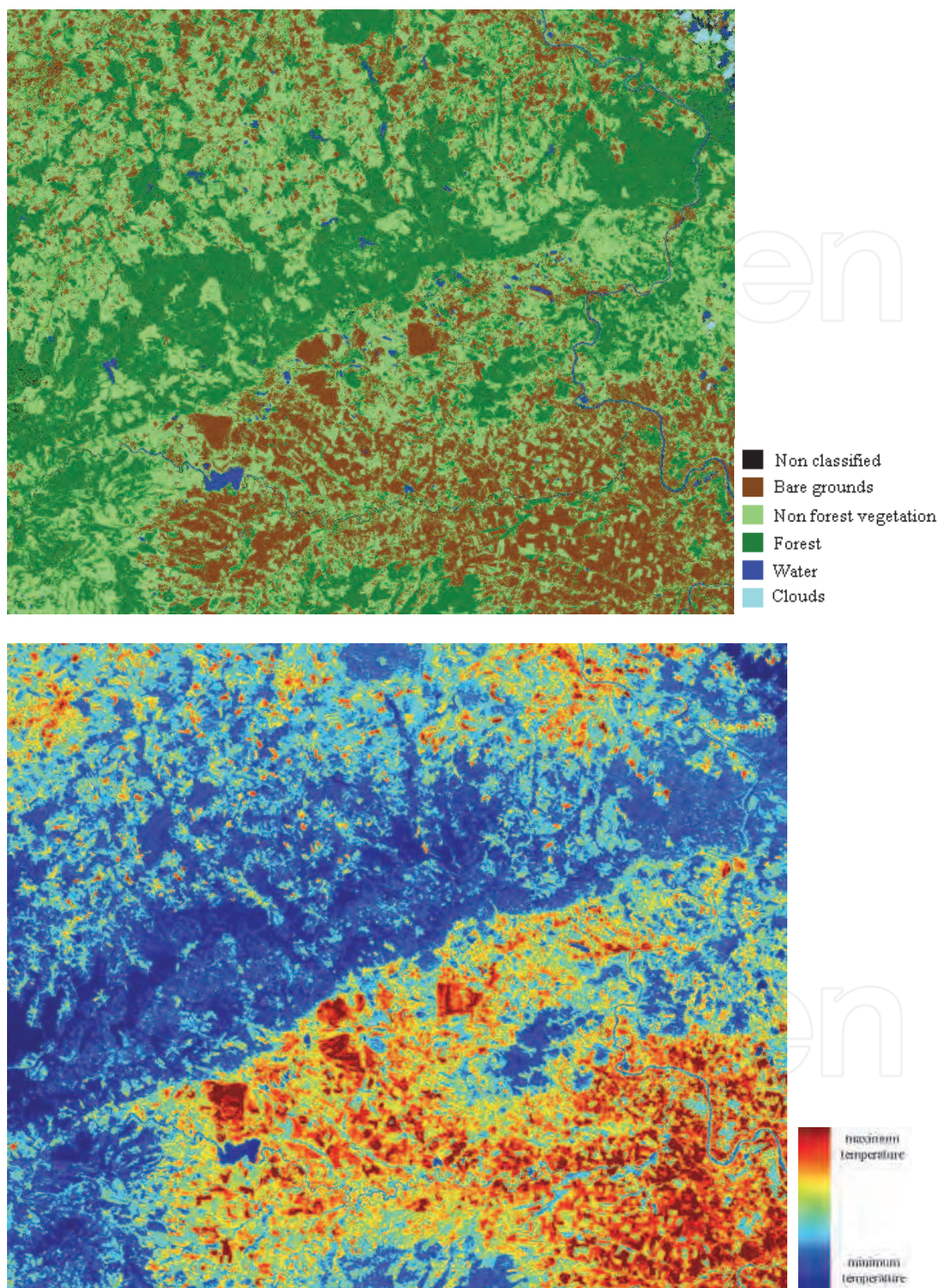


Fig. 8. Land cover (upper image) and temperature distribution (bottom image) over the model area of North-West Bohemia and Saxony obtained on 10 August 2004 at 9.40 GMT+1. The surface temperature data were obtained from Landsat thermal channel TM 6.

ability to convert (dissipate) the incoming solar energy; loss of vegetation is accompanied by changes in the distribution of solar radiation, resulting in a temperature rise. The lowest temperature range (20 – 22 °C) in both satellite scenes was obtained for a deciduous forest, followed by a coniferous forest (17 – 23°C) on the scene from the year 2004. In the satellite scene from 1995, the coniferous (spruce) forest across the top of the Krusne Hory mountains shows remarkably higher temperatures. This is explained by its lower cooling capacity, i.e. lower evapotranspiration rates, as, at that time, the forest was dying off due to the extreme depositions of sulphur dioxide emitted mainly in the 1980s. By 2004, the forest had mostly recovered and this can be seen through the recovery of the forest's cooling function and enhanced temperature damping. The highest temperatures (ranging between 31 – 45 °C) were found at the sites of open-cast brown coal mines and spoil heap tailings, but also on areas of arable fields after crop harvest (August 2004). Furthermore, this category of the highest temperatures, classified as bare grounds, also included urban areas, industrial and commercial zones, communication infrastructures (roads), as well as relatively natural surfaces such as rock outcrops, and peat bogs affected by drainage and/or peat mining. The temperature range of 23 – 32°C characterized the non-forest vegetation – a rather heterogeneous category of land cover that included meadows, areas with sparse vegetation, peatbogs and arable land in 1995 when this was still covered by green crops.

The temperature distribution over the prevailing different land uses depends on the water availability and rate of evapotranspiration. It illustrates the seasonal variability in the damping of temperatures over arable land: early in the season (satellite scene 1 July 1995; Fig. 7) when the crops are still green, the arable land belongs to the lower temperature class compared to the August 2004 scene (Fig. 8) when the crops had already been harvested and the sites fell into the highest temperature class, i.e. the sites were greatly overheated. Furthermore, we can observe the negative impact of the large arable fields of former state farms in the Czech Republic compared to smaller field sizes in Saxony (Germany) which show better temperature damping. The lack of functioning vegetation can be also seen in the shape of the temperature histograms (Fig. 6) – the histogram of 2004 is wider reflecting a higher spread of temperatures whilst the histogram of 1995 (with fields still mainly covered by crops) is narrower and shifted to lower values, reflecting the better cooling by vegetation. Sites with bare ground undoubtedly belong to the warmest places in the landscape; due to the lack of water evapotranspiration, more solar energy is transformed into sensible heat (raising the site's temperature) than into latent heat of water vapour. The higher albedo of bare ground (concrete, etc.) and the lower albedo of forests does not play such an important role when compared to the cooling effect of evapotranspiration (Pokorný et al. 2010a).

4.2 Mau Forest in Western Kenya

The Mau Forest complex, located about 150 km northwest of Nairobi, at an altitude between 1200 – 2600 m, is referred to as one of the largest remaining continuous blocks of indigenous forest in eastern Africa. With a high annual precipitation (reaching about 1000 mm on eastern slopes and more than 2000 mm on western ones) it is an area which includes the headwaters of many rivers feeding into the Rift Valley lakes (Lake Natron, Turkana, Victoria, Nakuru, Naivasha, Elmenteita and Baringo). In the last 25 years the site

has been subject to extensive deforestation: forest cover of 5200 km² in 1986 was reduced to a mere 3400 km² in 2009 (for details, see Fig. 9). The availability of satellite images since the 1980s has enabled us to demonstrate the effect the forest clearance has had on temperature distribution over the whole area. Extreme rises in temperature (by more than 20° C; see Fig. 10) can be observed on sites of deforestation. Its consequences are also evident in the Rift Valley region, between lakes Nakuru and Naivasha. Areas that have been converted into fast-growing plantation forest show the opposite trend, i.e., temperature damping.

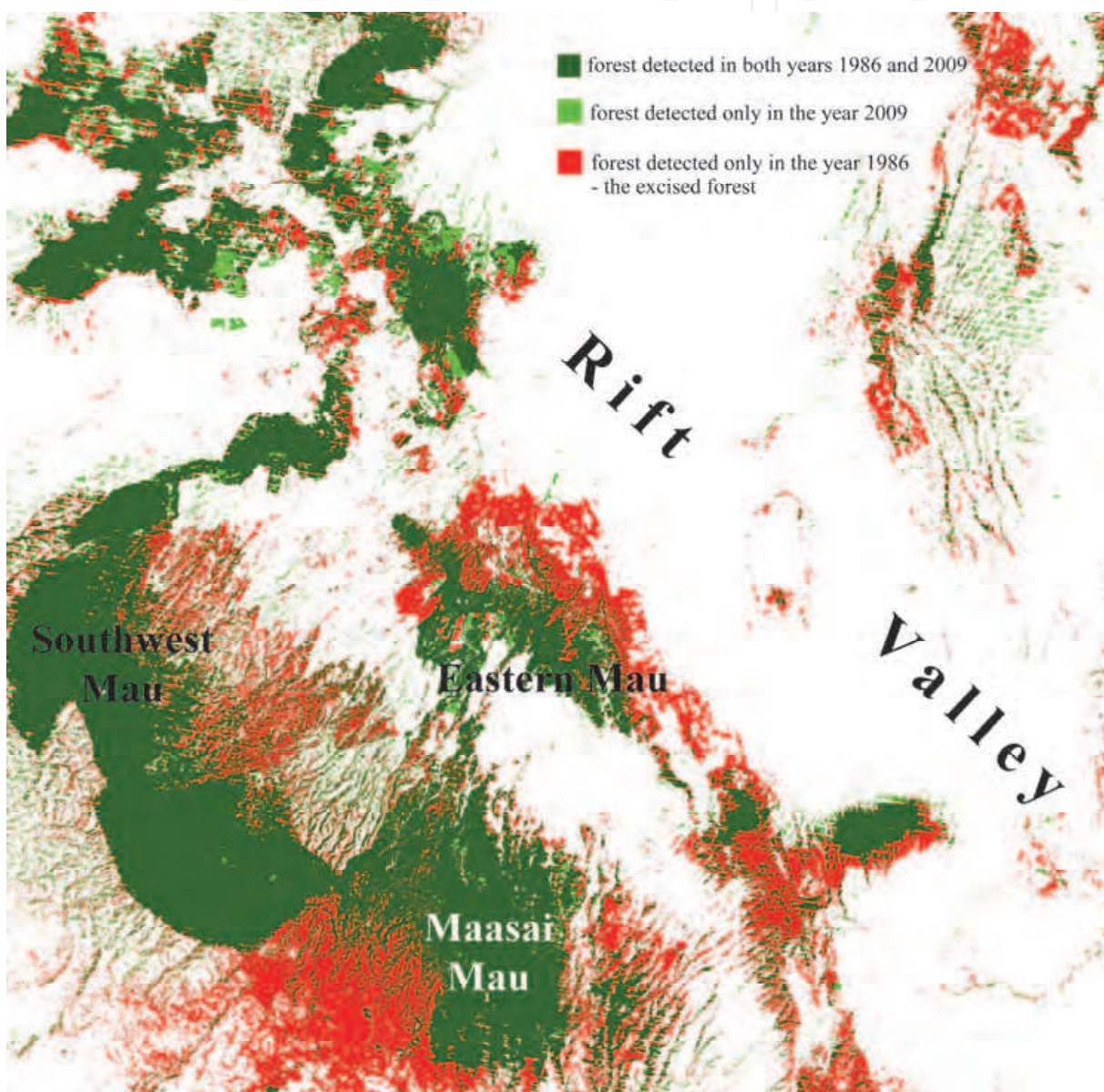


Fig. 9. Changes in the extent of the Mau Forest, East Africa, between the years 1986 and 2009.

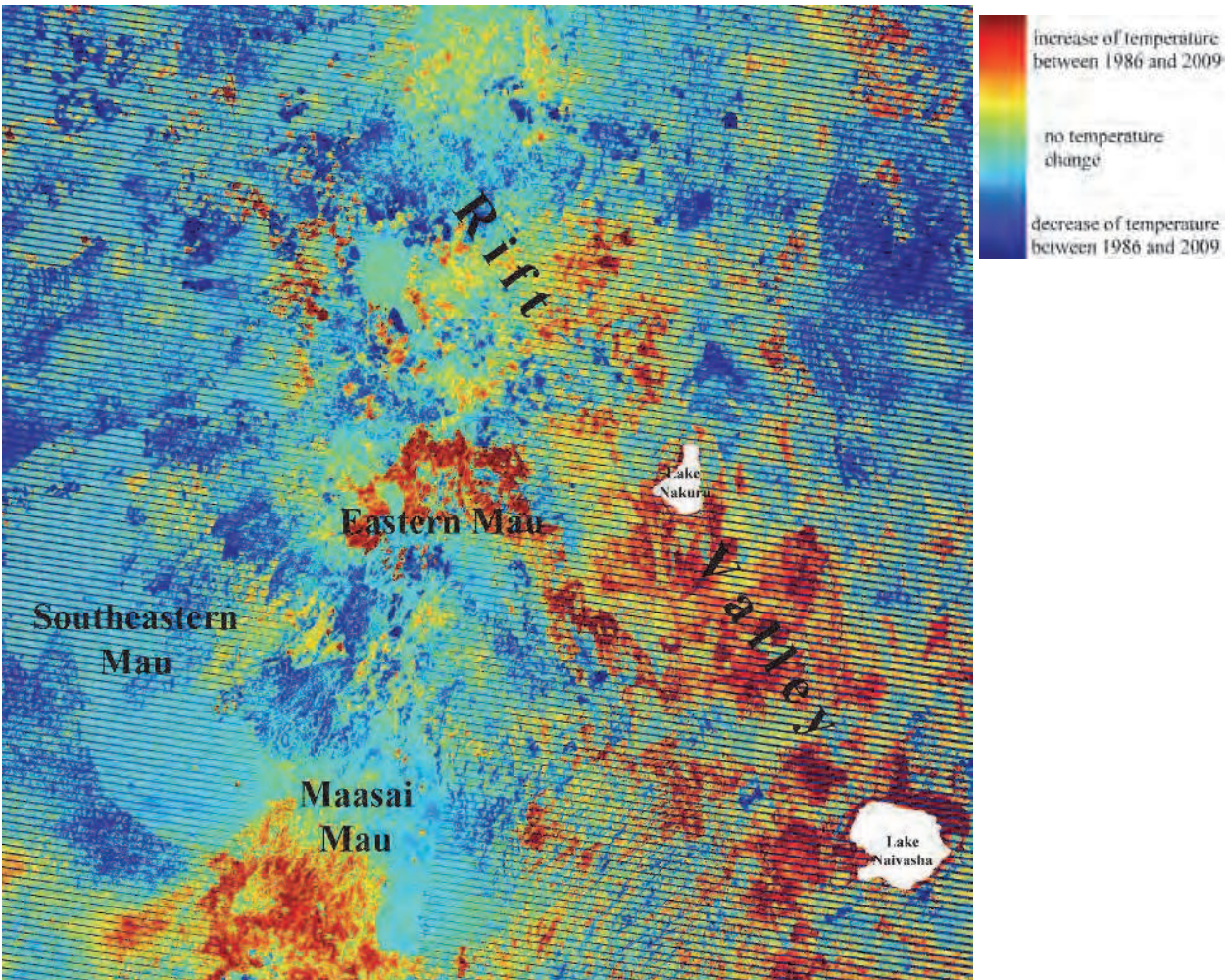


Fig. 10. Changes of temperature between the years 1986 and 2009 in the Mau Forest complex, East Africa, obtained as a difference of the standardized temperatures. The surface temperature data were obtained from Landsat thermal channel TM 6.

5. Discussion and conclusions

Deforestation and land drainage for agriculture or urbanisation has led to accelerated water discharge from catchments. From the self-regulating dissipative structures described earlier, loss of vegetation along with the water shortages has caused a shift to highly negative circumstances, with such consequences as temperature swings of

increased amplitude and frequency leading to turbulent motion in warm dry air. The loss of functioning vegetation has been extensive for some time, as observed and reported in the Millennium Environmental Assessment (2005): every year some 60,000 km² of badly managed land is becoming a desert and about 200,000 km² of land loses agricultural productivity. The lack of water and ecosystem functionality now affects 30–40% of our global landmass.

Life on land is only possible when soil contains enough moisture for green plants to grow. The continuous runoff of river water discharge from land to ocean needs to be compensated by the opposite transport of water vapour from ocean to continent. Makarieva and Gorshkov (2010) have shown the role of the forest cover in a condensation-induced water cycle that maintains a flow of moist air from ocean to continent. They evaluated precipitation measured along transects from ocean to land on different continents; they revealed that along transects with continuous forest cover precipitation reaches as far as 1000 km inland (in hardly diminished amounts), whilst above deforested landscape precipitation rapidly diminishes when distance from the ocean exceeds 600 km. They identified two principles as to how the forest attracts and retains water. Firstly, the forest vertical architecture induces a temperature inversion: during the day, temperatures in the forest understorey are lower than that of the forest crown; in this way losses of water vapour to the atmosphere are reduced. Secondly, at night, water vapour condenses above the forest canopy causing a decrease in air pressure above the canopy; this 'sucks in' air horizontally and can bring moist air from the ocean enhancing further water condensation above the forest. Induced by living organisms, this atmospheric circulation maintaining the hydrological cycle on land has been termed the 'biotic pump' of atmospheric moisture (Makarieva & Gorshkov 2007).

In addition to the long water cycle (ocean to land), the role of the short water cycle has been emphasized by Ripl (1995, 2010) as playing an important role in climate amelioration and landscape sustainability. Figures 7, 8 and 10 clearly demonstrate the role of a healthy forest in modulating surface temperatures contributing to climate amelioration. In contrast, the bare or scarcely-vegetated land with low water supplies is often overheated as a result of the reduced evapotranspiration. Furthermore, matter cycles are dependent on water circulation; water being the most important transport and reaction medium. Not only does vegetation largely control water runoff and precipitation over land - with the help of evapotranspiration - but it also controls matter flows. By controlling soil moisture, vegetation governs the process of organic matter decomposition and hence the circulation of matter. Over millions of years of evolution biological communities have optimized their self-organization to run a highly efficient resource economy and hence maintain their sustainability.

We have provided evidence that the sustainability of river catchments has been seriously impaired by large-scale deforestation and drainage. The accelerated discharge of water via rivers to the sea - caused by extensive deforestation, land drainage and hence the landscape's reduced capacity for water retention - brings about overly high matter losses. Data provided for Germany have shown that areal matter losses have reached between 1 and 1.5 tons of dissolved matter per ha per year on average (Ripl & Eiseltová 2009). Areas of high matter losses correlate with areas of reduced evapotranspiration, and hence landscape overheating, as shown in the detailed study of the Stör River

catchment in Germany (Ripl & Hildmann 2000) and three small sub-montane catchments in the Czech Republic (Procházka et al. 2001). The deforestation of large areas in tropical regions has resulted in a temperature increase of about 20°C (Hesslerová & Pokorný, 2010).

In arid zones, where irrigation is often a necessity for crop production, the situation is not better. Farmers may try to minimize the use of water for irrigation as water is scarce and costly; they will kill weeds by herbicides to reduce unwanted water losses through evapotranspiration. The ground thus remains void of an understorey or ground layer that would protect the soil from overheating, and rising hot air takes water vapour away. Even large irrigated areas, such as the cotton fields in Central Asia or irrigated farmland in Australia (e.g. the Murray-Darling Basin) do not achieve closed water cycles. Instead the excessive use of water for irrigation from rivers have had detrimental effects, such as the drying out of the Aral Sea due to water withdrawal from Amu-Darya and Syr-Darya (Central Asia) or the degradation of wetlands in the mouth of the Murray River in Australia. An additional problem is an increasing soil salinity in irrigated areas. There is an urgent need that agricultural research focuses on how to close water cycles in the landscape and the development of farming systems with a more vertically-layered vegetation structure keeping water and lower temperatures during a sunny day.

Observations of nature and studies of natural processes have offered us some understanding as to how nature tends to close the cycles of water and matter so that losses – water discharge and transport of matter via rivers to the sea – are kept to a minimum. We have provided evidence that evapotranspiration plays far the most important role in damping temperature amplitudes and helping to prevent large-scale overheating of land and atmosphere. Hence it is the vegetation cover that ameliorates the climate and can mitigate climate change. Studying the natural processes in a virgin forest in Austria has revealed how natural vegetation cover closes the cycles of water and matter and efficiently dissipates excesses in solar energy. An important question remains to be answered. How can we achieve such an efficient resource economy in a human-managed landscape - efficient water and matter recycling and energy dissipation as achieved by any undisturbed fully-functioning natural ecosystem? Below we offer some thoughts that we think are worth considering if society seriously wants to address landscape sustainability:

- An assembly of organisms that is ecologically-optimized will show the best local resource utilization in a given space; this ensemble will thus be the one that is able to grow and to expand over the area of that site. That is, at least, until some shift in the surrounding conditions immediately outside the given area should occur - and then another organism ensemble becomes the most efficient with respect to the available resources. According to the direct experience of farmers, the two mostly limiting factors for growth and expansion in our landscape are usually water and nitrogen.
- Farmers should be seen by society as the 'managers of our landscape': only their experience 'in tune' with their local environment - in direct feedback mode with the properties and harmonic patterns of their own locality - can rescue society's life-giving 'hardware', the land, and provide a sustainable management. The short water cycle -

with its inherent 'loss-free' matter flow - controlled by the land manager would appear to be the only way to a sustainable society. However, if intelligent land management is to be successful it has to be paid for: through appropriate rewards according to a land manager's achievements towards sustainability - such as low matter losses and efficient solar energy dissipation.

- All other conceptions of nature protection and conservation - that attempt some 'esoteric' protection of the landscape, with farmers trying to do 'nature conservation' by preserving structures in time and space - are in the long run deemed to fail. 'Fixed' structures cannot be sustainable within ecosystems that are living on dynamic changes towards keeping matter (biomass and soil) in place. Land management, as practiced today, that follows 'one rule fits all' centralized planning at the EU-level, must be seen as mismanagement; such planning results in an ever-growing disturbance of vegetation, climate, cooling and soil fertility, leading to steadily-growing desertification and loss of water, climate instabilities and increased food insecurities.
- There is not the slightest evidence for the belief that chasing the most necessary-for-life gas CO₂ through the trading of 'indulgence' certificates - and burying it deep down into what is mostly water-saturated zones - will change back a distorted climate. Neither has it been proved that, in an open atmosphere, CO₂ is acting as the driving greenhouse gas in the atmosphere as much as the far more dynamic water vapour under the aerodynamic conditions driving an ever-increasing number of wind-mills. To establish increasing areas of water evapotranspiration as the most desirable cooling mechanism, and dew formation as the most important process controlling air pressure in interaction with the vegetation cover of landscapes, would seem to be a far better strategy.

The water cycle is akin to the 'bloodstream' of the biosphere. Returning water to the landscape and restoring more natural vegetation cover is the only way to restore landscape sustainability. More attention in present-day science needs to be devoted to the study of the role of vegetation in the water cycle and climate amelioration. Restoration of a more natural vegetation cover over the landscape seems to be the only way forward.

Based on our current scientific knowledge, we can propose two criteria for assessing sustainable land management. These criteria are: the efficiency of an ecosystem to recycle water and matter; and its efficiency to dissipate solar energy. It is land managers that can substantially contribute to the restoration of the water cycle, climate amelioration and reduction of irreversible matter losses with river water flows to the sea. It is in the interest of society as a whole that land managers (farmers, foresters) be rewarded for their actions towards sustainable management of their land. Suitable tools to assess the achievements of individual land managers with respect to sustainable management of their land are: (1) continuous monitoring of conductivity - a measure of dissolved load - and flow rates in streams in order to estimate matter losses; and (2) the regular evaluation of satellite thermal channel images to assess temperature damping, i.e. the effectiveness of land use to dissipate solar energy. Restoration of natural 'cooling structures' - vegetation with its evapotranspiration and condensation-induced water circulation - is essential to renew landscape sustainability.

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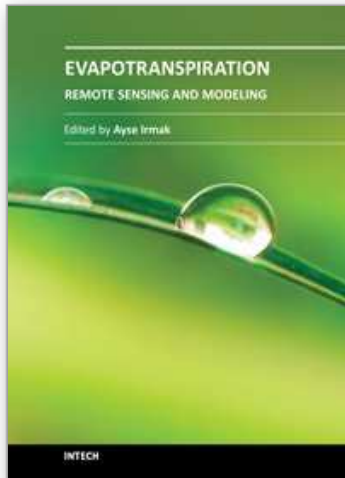
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This edition of Evapotranspiration - Remote Sensing and Modeling contains 23 chapters related to the modeling and simulation of evapotranspiration (ET) and remote sensing-based energy balance determination of ET. These areas are at the forefront of technologies that quantify the highly spatial ET from the Earth's surface. The topics describe mechanics of ET simulation from partially vegetated surfaces and stomatal conductance behavior of natural and agricultural ecosystems. Estimation methods that use weather based methods, soil water balance, the Complementary Relationship, the Hargreaves and other temperature-radiation based methods, and Fuzzy-Probabilistic calculations are described. A critical review describes methods used in hydrological models. Applications describe ET patterns in alpine catchments, under water shortage, for irrigated systems, under climate change, and for grasslands and pastures. Remote sensing based approaches include Landsat and MODIS satellite-based energy balance, and the common process models SEBAL, METRIC and S-SEBS. Recommended guidelines for applying operational satellite-based energy balance models and for overcoming common challenges are made.

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