Plant transpiration and net entropy exchange on the earth's surface in a Czech watershed

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Abstract The influence of plant transpiration on the entropy exchange was quantified as associated with the degradation of solar energy on the Earth's surface covered by plants. Two surfaces were studied: (1) productive surface – plant transpiration taken as equal to the potential one, (2) non-productive surface – plant transpiration taken as equal to zero. The entropy exchanges associated with the absorption of solar radiation and with the conversion of absorbed solar radiation into the sensible heat and latent heat were taken into account. These processes were examined in the experimental watershed Liz (828–1074 m a. s. l.) located in the Bohemian Forest (Czech Republic). We found that in the growing season 1992 the net entropy exchange in humid hydrologic period (the Earth's surface is productive) was considerably higher than in the arid one (the Earth's surface was productive in 39% of days, and non-productive in 61% of days). Considering that the biotic effect on the Earth's functioning can be measured with the help of the net entropy exchange, we can assume that the theory that biotic activities – represented by plant transpiration here – are the cause of the self-organizing processes in Earth's environment is proved in the watershed scale.

Key words: *hydrologic cycle, plant transpiration, entropy, Gaia theory*

Introduction

The Earth is a self-organized system. The source of information for self-organization is the degradation of solar radiation. The solar energy is highly organized and carried by photons. Earth absorbs this energy and then releases it back to the Universe. However, energy released to the environment is in the form of electromagnetic radiation, which is on average at longer wavelengths than the absorbed photons. The flow of the entropy associated with the energy conversion, which is at disposal for the self-organization, is approximately equal to 1.16×10^{38} bit s^{-1} (Roland-Mieskowski, 2007). The nature of self-organization is a theme of contemporary scientific discussion. The core of this discussion is the role of biotic processes (Kirchner, 2003; Volk, 2003a, 2003b). Lovelock and Margulis formulated a theory (Lovelock, Margulis, 1974) that the self-organization in a global scale is an emergent characteristic of the Earth's biota (Gaia theory). The biotic effect on the Earth's functioning can be measured with the help of the net entropy exchange associated with the solar energy conversations on the Earth's surface (Kleidon et al., 2000; Kleidon, 2002, 2006; Kleidon, Lorenz, 2004; Lenton, Wilkinson, 2003).

Many authors tested the self-organizing processes caused by biotic effect – plant transpiration. The solar illumination as a cause of self-organizing processes by evaporation of water from leaf parenchyma was shown by Tributsch et al. (2005) at the micro-scale of water molecules. Dissipation of solar energy in landscape – controlled by management of water and vegetation – was identified as a cause of the ecosystem control at the global scale (Ripl, 1995; Pokorný, 2001; Šír et al., 2004). Transpiration has a great influence on the soil and air temperature (Tesař et al., 2006). Climatic data obtained in the Czech mountains showed that notwithstanding the incidence of solar radiation on plant cover, plant surface temperature did not exceed certain maximum temperatures (about 25ºC) when plants transpired. During the periods with full transpiration the air temperature did not exceed 25ºC. Scarcity of water for plant transpiration caused decreasing plant transpiration, which resulted in an important increase of plant, soil and air temperature. In the periods with insufficient transpiration the plant temperature of plant surface reached approximately 35ºC, and air temperature approximately 30ºC.

Based on this finding a theory of plant transpiration was formulated (Pražák et al., 1994): plants protect themselves against overheating above the optimum temperature by the transpiration – i.e. by the heat uptake for water vaporization. It was found that a plant behaves as a regulator, when transpiration is set on if absorbed solar energy heats up the plant above some optimum temperature, and set off, if the plant temperature falls below this value. This regulation fails when water is not available for plants (Novák & Havrila, 2006). It was proved that scarcity of water for plant transpiration can be evaluated using measured tensiometric pressure in the root zone of the soil cover. The limiting value of tensiometric pressure, below which the water uptake for plant transpiration is impossible, was –60 kPa for grass and spruce vegetation over many growing seasons (Šír et al., 2004). If plants transpire, absorbed solar energy is divided into two parts – latent heat (used for water vaporization) and sensible heat (emitted from the warmer plant surface into the cooler atmosphere). If plants do not transpirate, the latent heat is equal to the zero.

According to Kleidon (2002) two zero hypotheses are formulated: (1) Antigaia hypothesis – biotic effects do not increase the net entropy exchange, (2) Gaia hypothesis – biotic effects increase the net entropy exchange. The hypotheses are tested using a simplified model of the productive/non-productive surface. The ground surface covered with fully transpiring surfaces (when actual transpiration is equal to the potential one) is called „productive". In the case when transpiration ceases, the surface is called „non-productive". Our approach was motivated by the concept of a green planet versus a desert world described in the article Kleidon et al. (2000). Two extreme forms of the hydrologic period were studied: (1) the humid hydrological period – the Earth's surface is productive during the whole growing season, plant transpiration is equal to the potential one, i.e. water vaporization is governed by plants and water shortage does not represent any limiting factor, (2) the arid hydrologic period – the Earth's surface is productive or non-productive depending on the water availability for plant transpiration. Water availability (measured with the help of tensiometric pressure in the root zone of the soil cover) for plant transpiration was taken into account in the arid period only.

Our article is a contribution to the testing of the self-organizing processes caused by biotic activities through plant transpiration.

Experimental area

The experimental watershed Liz is located in the Bohemian Forest about 2 km aerial distance southwest from the village of Zdíkov, in the Czech Republic. The fully forested watershed is covered by mature spruce forest. The soil cover (acid brown soil) is composed of several horizons with different hydraulic properties, but the infiltrated water largely flows downwards through the soil, so that surface and subsurface runoff are rare phenomena. Highly permeable subsoil forms a shallow drainage layer transporting water from the soil to a small brook. This layer is not fully filled with water, so that no significant areas with ground water table are in the watershed. Geological bedrock (paragneiss) forms an impermeable layer. The experimental area was described elsewhere (Pražák et al., 1994). The area of the watershed is covered by automated monitoring network equipped with sensors for measuring precipitation, air temperature at two levels, soil temperature at five depths, tensiometric pressure at four depths and volumetric soil water content at three depths, and the discharge in the closing profile of the watershed.

The basic watershed characteristics are: elevation is within 828–1074 m above sea level, drainage area is 0.99 km^2, average slope is 17 %, precipitation total is 851 mm/year, runoff depth is 324 mm/year, mean discharge is 0.01 m^3/s, and the mean annual air temperature is 6.3 ºC. The typical soil water retention capacity (i.e. the difference between maximum and minimum soil water content) is about 60–90 mm. Climatic characteristics of the typical growing season were as follows: the duration was 27.5.–30.9. 1995, the precipitation sum was 544 mm, the potential transpiration sum was 222 mm, the mean air temperature from 5 a.m. till 8 p.m. was 12.1ºC, and the global radiation sum was 2297 MJ m^{-2}.

The Gaia/Antigaia hypotheses were tested in the extremely warm and dry growing season of 1992 in the Liz catchment. Climatic characteristics of the season were as follows: the duration was 27.5.–30.9.1992, the precipitation sum was 204 mm, the potential transpiration sum was 310 mm, the mean air temperature from 5 a.m. till 8 p.m. was 14.3ºC, the global radiation sum was 2210 MJ m^{-2}. In the 1992 growing season the net entropy exchange in the Liz catchment was quantified in arid and humid hydrologic periods. The arid hydrologic period represented a situation when in 39% of days the Earth's surface was productive, in 61% of days was non-productive, i.e. plant transpiration was equal to zero. The humid hydrologic period represented a situation when plant transpiration was equal to the potential one. The value of the optimum temperature was 25ºC in the case of the productive surface. The same values of global radiation, air temperature, and albedo were used for the calculations of the humid and arid period.

Methods

The objective of this study was to evaluate a relation among temperature of plant cover, latent heat used for transpiration, and sensible heat irradiated from plant to the atmosphere using the net entropy exchange on the plant surface. Measured values of global radiation, air temperature and water availability for plant transpiration in the Liz experimental watershed (Bohemian Forest, Czech Republic) during the growing season 1992 were used for testing.

Three processes in which the solar energy is converted on the Earth's surface are studied from the point of the entropy exchange: The absorption of the solar energy on the surface, the irradiation of the sensible heat from the surface, the uptake of the latent heat for water evaporation from the surface. The entropy exchange e_G (W m^{-2} K^{-1}) associated with the absorption of solar radiation on the surface is given by:

$$e_G = a\, G/T_{Sun} \tag{1}$$

where G (W m^{-2}) is the flux of global radiation, a (–) is effective absorptivity, and T_{Sun} = 5760 K is the absolute temperature of the Sun (Kleidon & Lorenz, 2004). The entropy exchange e_H (W m^{-2} K^{-1}) associated with the sensible heat flux across the boundary productive/non-productive surface – atmosphere is given by:

$$e_H = H/T \tag{2}$$

where H is the sensible heat flux (W m^{-2}), and T (K) is the absolute temperature of the surface from which the sensible heat is irradiated. The entropy exchange e_L (W m^{-2} K^{-1}) associated with the latent heat flux across the boundary productive/non-productive surface – atmosphere is given by:

$$e_L = L/T \tag{3}$$

where L is the latent heat flux (W m^{-2}), and T (K) is the absolute temperature of the surface from which the latent heat is taken for evaporation. The net entropy exchange e (W m^{-2} K^{-1}) associated with the studied solar energy conversations on the Earth's surface is given by:

$$e = e_H + e_L - e_G \tag{4}$$

where e_G, e_H, e_L are given by Eqs (1) to (3). It should be mentioned that the entropy exchange is evaluated for each day from 5 a.m. till 8 p.m. In this sunny period, other long-wave heat fluxes and associated entropy exchanges on the Earth's surface (e.g. heating up of the soil covered by dense vegetation) are negligible as compared to the quantities in Eq. 4.

A model of surface heating/cooling (Pražák et al., 1994) was used for calculations of quantities in Eqs (1) to (3) for productive and non-productive surface. The model is parameterised using an optimum temperature T_o (ºC), albedo a (–), and effective thickness l (m) of the surface (leaf), and limiting value R of tensiometric pressure in the root zone of soil below which the water uptake for transpiration is impossible. Input data are the time courses of the air temperature T_a, global radiation G, and tensiometric pressure h (kPa) in the root zone of the soil. The model outputs are the temporal course of potential transpiration PET (m s^{-1}), actual transpiration ET (m s^{-1}), latent heat L (W m^{-2}) and sensible heat H (W m^{-2}) fluxes, and the time course of surface temperature T (ºC) for productive/non-productive surface.

The model was calibrated in the Liz catchment in both situations when the plant cover transpired and did not transpire (Pražák et al., 1994; Tesař et al., 2001). The quantities characterising both the productive and non-productive surface obtained by the calibration procedure were: T_o = 25ºC, a = 0.75, l = 0.001 m. The limiting value of tensiometric pressure splitting situations when the surface behaved as productive and non-productive was R = –60 kPa.

Input data G, T_a and parameter values T_o, a, l used for calculations of net entropy production in the season 1992 on the Liz catchment, were identical for the productive and non-productive surfaces. Physical constants, used in calculations, were set as follows: the density of water is 1000 kg m^{-3}, the specific thermal capacity of the leaf is 4200 J kg^{-1} K^{-1}, and the specific latent heat of vaporization is 2.3x10^{6} J kg^{-1}.

Results

The results for the whole growing season (27.5.–30.9.1992) are shown in Table 1 and Figs 1–4. The net entropy exchange was estimated for each day from 5 a.m. till 8 p.m. The net entropy exchange in the humid hydrological cycle was higher in 1% than the net entropy exchange in the arid cycle. In an extreme warm day it was higher in 2.4%.

The evaluation of the net entropy exchange in the humid cycle included a small inconsistency of meteorological data. These data were measured in the situation when in the 39% of the days the plant transpiration was strongly limited by water shortage. But they were subsequently used in an unchanged form for calculations of entropy exchange in the humid cycle when the plant transpiration was not limited by water availability. As a result it is evident, that the air temperature, global radiation and precipitation are linked to the plant transpiration. This link is omitted in this phase of work because no appropriate data or theories were yet available.

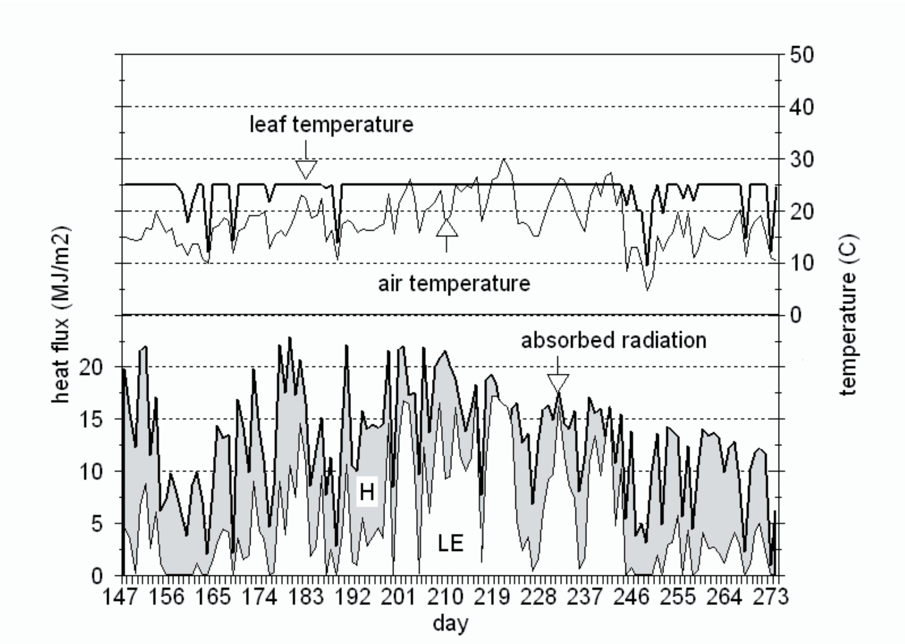

Fig. 1. Daily maximum of leaf and air temperature, daily sum of absorbed global radiation and its splitting into latent (LE) and sensible (H) heat in the growing season (27.5.–30.9. 1992) from 5 a.m. till 8 p.m. in the humid period.

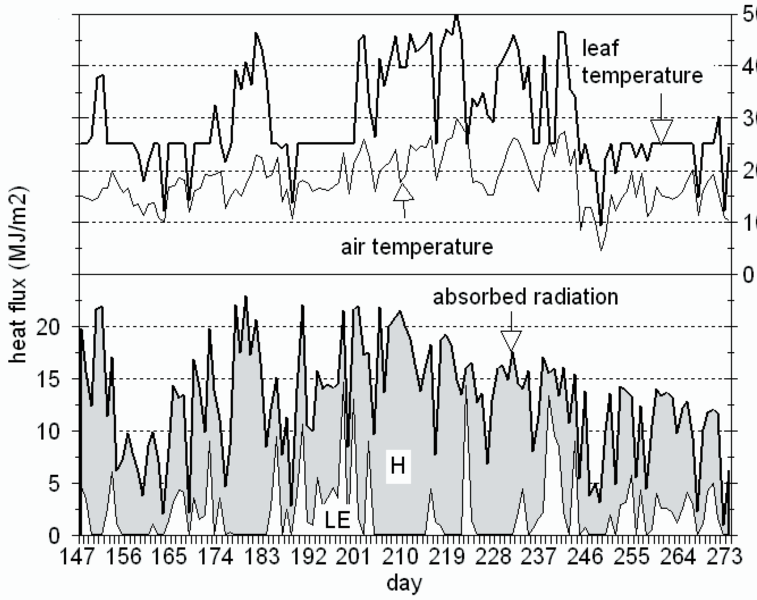

Fig. 2. Daily maximum of leaf and air temperature, daily sum of absorbed global radiation and its splitting into latent (LE) and sensible (H) heat in the growing season (27.5.–30.9. 1992) from 5 a.m. till 8 p.m. in the humid period.

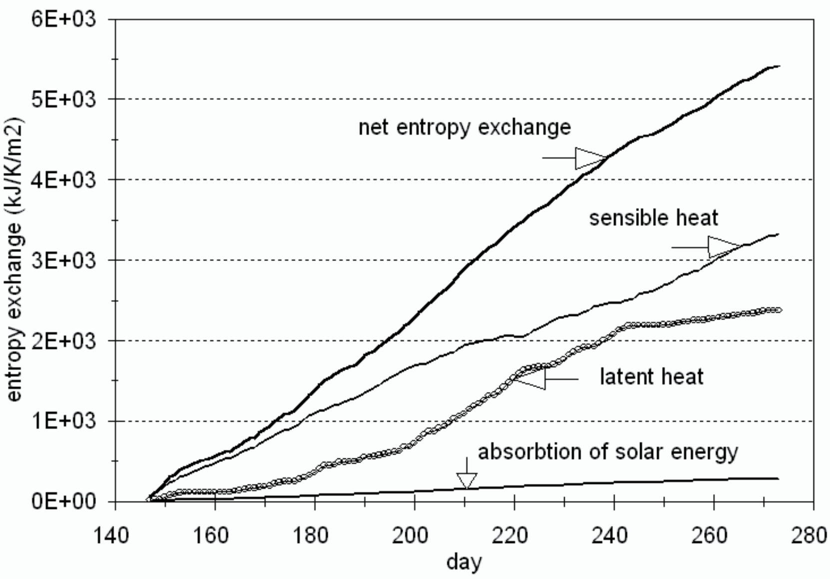

Fig. 3. Mass curve of the net entropy exchange in the growing season (27.5.–30.9. 1992) from 5 a.m. till 8 p.m. in the humid period.

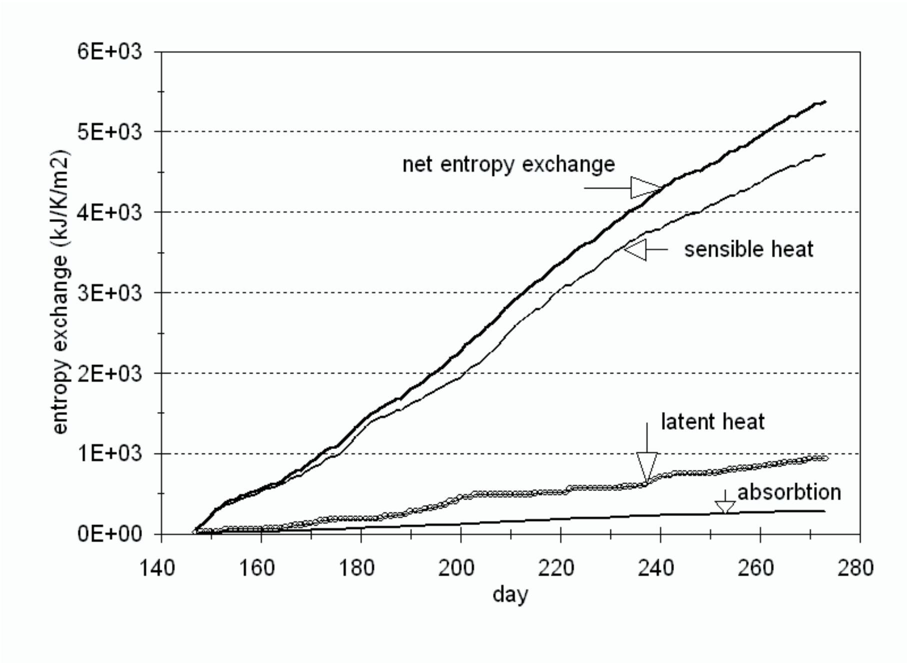

Fig. 4. Mass curve of the net entropy exchange in the growing season (27.5.–30.9. 1992) from 5 a.m. till 8 p.m. in the arid period.

Table 1: Net entropy exchange in the 1992 season (27.5.–30.9.1992).

27.5.– 30.9.1992 from 5 a.m. till 8 p.m.	humid cycle	arid cycle
Potential transpiration PET (mm)	310	310
Actual transpiration ET (mm)	310	121
ET/PET (–)	1	0.39
Max. leaf temperature (ºC)	25.0	50.7
Latent heat (MJ m^{-2})	698	274
Sensible heat (MJ m^{-2})	958	1382
Sum of entropy exchange – latent heat (kJ $m^{-2} K^{-1}$)	2378	938
Sum of entropy exchange – sensible heat (kJ $m^{-2} K^{-1}$)	3329	4719
Sum of entropy exchange – absorption (kJ $m^{-2} K^{-1}$)	285	288
Sum of net entropy exchange (kJ $m^{-2} K^{-1}$)	5422	5369

Discussion and conclusions

The net entropy exchange in the humid hydrological cycle was higher in 1% than the net entropy exchange in the arid cycle (Table 1). It means that the Gaia hypothesis is proved as valid in this case, which corresponds to the finding that the natural selection of optimum temperature of plant cover tends to produce the maximum amount of phytomass (Šír et al., 2004). At the global scale, this would imply subsequently that the net entropy exchange across the boundary of Earth's surface – atmosphere is maximized and the entropy of mass accumulated on the Earth's surface is minimised in case that the surface is covered by transpiring plants.

Considering that the biotic effect on the Earth's functioning can be measured with the help of the net entropy exchange, we can assume that the theory that biotic activities – represented by plant transpiration here – are the cause of the self-organizing processes in Earth's environment is proved in the watershed scale. This conclusion corresponds to the findings published in the article by Kleidon et al. (2000).

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