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Temperature and humidity characteristics of two willow stands, a peaty meadow and a drained pasture and their impact on landscape functioning

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Shrubs and herbal wetland stands have a very important influence on microclimatic conditions and short water cycling. However, they have received very little attention. This study concerns with the role of willow and peaty meadow stands and a mesic pasture in their ability to affect both the temperature and energy regime. Our results showed that the pattern of daily temperatures (diurnal variation and temperature amplitudes) were more balanced in the wetland stands than in the pasture. The most attenuated and stable temperatures were measured in the willow stands whereas the fastest warming of the soil substrate occurred in the peat meadow. Temperature amplitudes and differences in daily average temperatures on the stand surfaces increased with decreasing air humidity. Thermographic camera pictures showed that in the peaty meadow the means of stand surface temperatures as well as daily temperature oscillations were higher than in the willow stand. Although no significant statistical differences were found, daily time series of the Bowen ratio showed an increase towards midday in the willow stand. This was presumably the result of a midday depression of transpiration. We determined that more solar energy was converted into latent heat than into sensible heat in both wetland stands. Therefore we suggest that these wetland stands function in the landscape as functional dissipative ecological units.

Introduction

Solar energy, which comes onto the land surface in seasonal and diurnal pulses, is dissipated into four main fluxes: reflection, sensible heat, latent heat and ground heat flux, where vegetation and water represent the interface responsible for the spatio-temporal patterns of solar energy dissipation. Whilst primary production is obviously vital in maintaining that interface represented by vegetation (and water), energy dissipation as expressed in terms of solar energy bound in biomass is not really involved in the four main fluxes as it represents less than 1% of the total annual solar energy income on a plant stand.

The ratio of sensible to latent heat (Bowen ratio) shows whether incident solar energy is used mainly for water evaporation or released in the form of sensible heat. Wide daily amplitudes of temperature both in a plant stand and the adjacent atmosphere indicate a relatively low evapotranspiration (i.e. a small latent heat flux). Areas with an insufficiency of water and land bare of vegetation typically show wide extremes in diurnal temperatures. As a result of insufficient temperature damping by water vapour, heat potentials develop in the landscape both in time (daily and seasonally) and space ('hot spots'), which can result in an increase in wind velocity, transport of dust into the atmosphere and changes in precipitation patterns (Ripl 1995, Pokorný 2001a, Ripl 2003). The ever-increasing removal of natural vegetation and its replacement with agriculture crops (and urban landscapes) and the acceleration of wetland drainage have caused water tables to decrease and an unregulated heating of the land surface. The resulting increased rates of organic matter decomposition in soils, and the associated depletion of soil fertility through accelerated losses of nutrients, namely base cations (Ripl 1995, Pecharová *et al*. 2001), are further results of land drainage. From this point of view, vegetation saturated with water plays a crucial role in water and matter retention in a given landscape/catchment, and mitigates against climatic extremes (Ripl 1995, Procházka *et al*. 2001, Pokorný 2001b, Ripl 2003). Recent studies have mostly focused on energy balance and evapotranspiration at the ecosystem level, over relatively large areas (e.g., Přibáň and Ondok 1980, Valentiny *et al*. 2000, Kellner 2001, Eaton *et al*. 2001, Wewer *et al*. 2002, Pivec 2002, Yamazaki *et al*. 2004). Energy balance at the landscape level has been studied mostly in agricultural landscapes in connection with the irrigation of arid areas (e.g., Lascano 2000, Brown *et al*. 2001, Ben-Gal and Shani 2002). Relatively little literature can be found on the dissipation of solar energy by stands of certain dominant species in natural ecosystems (e.g. Jeník *et al*. 1984, Přibáň *et al*. 1992, Burba *et al*. 1999, Clevery *et al*. 2002, Eitzinger and Kössler 2002).

Little attention has been paid to the role of plants (herbs and shrubs) in the formation of a microclimate in wetlands by way of the dissipation of solar energy through a fully-functioning short–circuited atmospheric water cycle.

The aim of this study is to compare three different habitats — willow shrub, peaty meadow and drained pasture — in terms of selected micrometeorological aspects (temperature, relative humidity and Bowen ratio) and to show their possible relation to the short-circuited atmospheric water cycle and dissipation of solar energy in wetlands. Standard microclimatic measurements of air temperature and relative humidity were accompanied by a thermal camera description of temperature distribution over the area of the monitored plant stands. The following questions concerning the role of water and vegetation in the dissipation of solar energy were asked: (i) Is the course of daily temperatures and daily temperature amplitudes more stable and more even in the willow stands in each vertical profile during the vegetation season and during sunny days than in the peaty meadow and in the drained pasture? (ii) What differences in temperature characteristics are there between the peaty and willow stands in relation to changes in relative air humidity? (iii) Is the ratio between sensible and latent heat (the Bowen ratio, expressed as the ratio between temperature and water vapour pressure differences) shifted more to latent heat in the willow stands than in the peaty meadow? Is the evaluated daily course of Bowen ratios in the willow stand and the peaty meadow different?

Material and methods

Study site

The study site is situated in the southeastern part of the Bohemian Forest in the Šumava Biosphere Reserve (Czech Republic) and belongs to the southeastern promontory of the Trojmezná ridge called the Svatotomášské pohoří/mountain range (Czudek *et al*. 1972). In geological terms, the study site belongs to the Moldanubicum — this is an historical name for the region of central Europe which is composed of crystalline and metamorphic rocks, 300–380 million year old (Chábera 1978) with acidic brown soils (cambisol).

The site belongs to a mildly cold region with an annual mean temperature of 5.5 °C and total annual precipitation of 910 mm. During the vegetation season, the average temperature is 11.2 °C and precipitation 550 mm. Most precipitation occurs during the summer months, minimum precipitation is in January and February. The average number of days with snow cover is 110, average maximum height of snow cover is 0.7 m.

Two willow stands and a peaty meadow were selected in the floodplain of the Horský potok stream (48°37.426´N, 14°06.804´E) and a mesic pasture was selected in the floodplain of the Mlýnský potok stream (48°35.950´N, 14°07.297´E) — as objects both of monitoring and experiment. The three selected areas are comparable concerning their slope, altitude and aspect.

The floodplain of Horský potok (Mountain stream) represents a diverse mosaic of wetland herb and shrub vegetation.

Hybrids of *Salix cinerea* × *Salix aurita* form both willow stands. The soil consists of acidic brown soil (cambisol) enriched with intensely-accumulating humus and peat. The first willow stand (I) consists of shrubs about 5 m high with ground diameters of 12 m, the other (II) consists of shrubs about 4 m high and ground diameters of 8 m. Leaf area index (LAI) and specific leaf area were determined using destructive analysis of one willow shrub on 28 August 2002: LAI = 4.7 m^2 m^{-2} and specific leaf area 17.1 m^2 kg^{-1} dry mass. Though these data are only informative, but we suppose the similar LAI characteristics for other willow shrubs in the observed locality. The amount of energy bound in the leaf biomass was measured directly in the laboratory with a calorimeter (IKA C 200, Germany). The estimated value was 18.04 kJ g^{-1} dry mass, i.e. 1055.34 kJ m^{-2} leaf area.

The peaty meadow is comprised of a stand of the suballiance *Calthenion* with dominant *Carex rostrata* developing towards a transient bog with *Sphagnum* sp.

The pasture comprises a mesic grass stand of the alliance *Cynosurion* with dominant *Agrostis capillaris, Trifolium repens*, *Festuca pratensis* and *Poa pratensis*.

The willow stand and the peat bog are situated in a relatively narrow floodplain at the headwaters of the Horský potok stream.

The soil types of all studied stands belong to the acid brown soils (cambisol). A layer of organic soil is formed from plant detritus in the willow stands and especially in peaty meadow.

Data description

The data were collected during the vegetation season 2002 in two time periods: from 7 June to 15 July and from 17 August to 19 September. In the first period, temperature was monitored at 1 hour interval series at four levels (1.5 m above the stand, at the stand surface, at the soil surface and 0.15 m below the soil surface) within the four stands: two willow stands, a peaty meadow and a drained pasture. In each stand one meteo-station was installed. The daily data of the first period were used for calculation of daily temperature amplitudes. For comparison of the stands the data of all days and of selected sunny days only (13, 14, 15, 17, 18, 19, 20, 21, 23, 27 June and 5, 8, 9 July) were evaluated.

In the second period, 15 minute interval series of temperature (°C) and relative air humidity (%) in a willow stand and in the peaty meadow at a stand surface and 1.5 m above the stand surface were measured. The Bowen ratio time series were computed from these data. Furthermore, these data were used for comparison of differences between stand surface temperatures in dependence on the relative air humidity. For these purposes data from the period between 17 August and 19 September (8:30–18:30) were evaluated.

Willow and peaty meadow stands were scanned by the thermographic camera every 10 minutes during a cloudless and sunny afternoon of 28 August 2002 (13:15–14:35).

The records from thermographic camera could be characterised as spatial. Although the temperature and relative humidity electronic sensors could be characterised as point values, the information we get from them reflects the temperature and humidity characteristics of the whole surrounding. The surface area monitored by the sensors is dependent on the distance of the sensor from the stand surface (Stannard *et al*. 2004). A sensor located 1.5m above the stand surface reflects temperature of several hectares whereas the sensor placed at the stand surface

Table 1. Description of recorded data. W I and W II = willow stands, M = peaty meadow, P = drained pasture.

	Locality	Date of measurement	Measurement interval	No. of days
Temperature (°C) 1.5 m above stand surface	W I., W II., M, P	7.VI.–15.VII. and 16.VIII.–20.IX.	1 hour; 15 min	39; 35
Temperature (°C) at the stand surface	W I., W II., M, P	7.VI.–15.VII. and 16.VIII.–20.IX.	1 hour; 15 min	39; 35
Temperature (°C) at the soil surface	W I., W II., M, P	7.VI.–15.VII.	1 hour	39
Temperature (°C) 0.15 m below soil surface	W I., W II., M, P	7.VI.–15.VII.	1 hour	39
Relative humidity (%) 1.5 m above stand surface	W I., M	16.VIII.–20.IX.	15 min	35
Relative humidity (%) at the stand surface	W I., M	16.VIII.–20.IX.	15 min	35
Radiative temperature (°C) (measured with thermo-camera)	W, M	28.VIII.	10 min	1

measures temperature of several square meters. The overview of recorded data is described in details in Table 1.

Temperature and humidity characteristics

Air temperature and air humidity were both measured in the selected stands. Time series of temperatures were monitored at four vertical levels of the stand profile (0.15 m below soil surface, at soil surface, at the stand surface and 1.5 m above the stand) using Pt 1000 resistor thermometers and the measured values recorded by dataloggers L0141 Comet System (Czech Republic) at 15-min intervals with ±0.2 °C accuracy.

A thermographic infrared FPA (focal plane array) camera ThermaCAM™ PM695 (Flir System, Sweden) was used for temperature mapping of the willow stand and the peaty meadow. The thermographic camera works in the infra-red between 7.5–13.5 μm wavelengths with 0.1 °C accuracy. ThermaCAM™ Reporter 2000 Professional software was used for evaluation of the pictures.

To assess possible correlations between temperature changes in the stands and precipitation, daily data on precipitation were used as provided by the CHMI (Czech Hydrometeorological Institute, which provided precipitation measurements only) from the Svatý Tomáš Station (980 m a.s.l.) for the year 2002. This meteorological station lies only 2 km from the study sites on the peaty meadow and willow stands and 4 km from the pasture.

Relative air humidity was measured with T+RH sensors (Comet System, Czech Republic) with ±2.5% accuracy in the 5%–95% range. The relative humidity probes were covered with sinter cover. The values were recorded by the loggers R3121 (Comet System, Czech Republic) every fifteen minutes as per the temperature logging.

Bowen ratio

To evaluate the balance between the sensible and latent heat fluxes in both the willow stand and the peaty meadow, the Bowen ratio was used, calculated as (Thom 1975):

$$\beta = \gamma\left(\frac{\Delta T_{\mathrm{a}}}{\Delta e_{\mathrm{a}}}\right) \quad (1)$$

where γ is the psychrometric constant (0.066 kPa K^{-1}), ΔT_{a} is the difference between the temperature 1.5 m above the stand and that at the stand surface, Δe_{a} is the difference of water vapour pressure (kPa) in these two respective layers.

The Bowen ratio is the ratio between the sensible and latent heat fluxes ($\beta = H/\mathrm{LE}$), both of which form part of the energy balance equation (Penman 1948):

$$R_n = G + H + \mathrm{LE} \quad (2)$$

where R_n is net radiation (W m^{-2}), H is sensible heat flux (W m^{-2}), LE is latent heat flux (W m^{-2}) and G is ground heat flux (W m^{-2}). In this study, the energy balance approach was not used, because energy fluxes were not measured.

The values of water vapor pressure e_{a} (mm) were calculated by the formula:

$$e_{\mathrm{a}} = R_h e_{\mathrm{w}}/100 \quad (3)$$

where R_{h} is relative air humidity and e_{w} is the saturation pressure of saturated water vapour (kPa) in the air for the given temperature. Values of e_{w} were computed using the modified empirical equation (Buck 1981):

$$e_{\mathrm{w}} = 0.61121\exp\left(\frac{17.502t}{240.97 + t}\right) \quad (4)$$

Horizontal fluxes of energy (advection) were not measured. Extreme and nonsense values of the Bowen ratio were not used in our subsequent calculations. Such extreme values of the Bowen ratio were estimated mostly between 9:00 and 11:00 and between 19:00 and 20:00.

In spite of the relative inaccuracy of the Bowen ratio measurement, we consider it as a simple, cheap but sufficient indicator for evaluating the role of various stands in terms of the dynamics of the transformation of incoming solar energy.

Statistical analyses

The data were analysed using STATISTICA 6.0 software (StatSoft Inc. 2001). One-way within-subject ANOVA was used for testing the differences among the habitats (*see* Appendix).

For testing temperature series data measured at 1-h intervals, a nested design was employed. The time records were nested in stands. The assumption was that the stands do not statistically differ in hourly temperature characteristics within a vertical level. Requirements of the ANOVA were tested. The data had normal distribution, howewer the homogeneity of variance was violated. According to Lindman (1974, cited in StatSoft Inc. 2001), the F statistic in the within-subject models is robust against violations. Large number of measurements can cause problems with strength of the test. However, our data sets were divided into groups according to the differing times of measurement and so the number of compared values was reduced. For testing the differences between the time series of daily temperature amplitudes measured in the stands, the within-subject design was used. Habitats were used as treatments and times of measurement were used as blocks. The null hypothesis for the characteristics of the time series of daily temperature amplitudes was as follows: within a vertical level, the stands do not significantly differ in the characteristics of the average amplitudes of daily temperatures.

Subsequently, after testing the differences between stands with the ANOVA, the combinations of Student's paired t-test were used. In order to keep the probability of Type I error on the nominal significance level a Bonferroni correction was applied: $\alpha_{\mathrm{used}} = \alpha_{\mathrm{nominal}}/C$ (Salkind 2007), where α_{used} was a corrected significance level, $\alpha_{\mathrm{nominal}}$ was a nominal significance level and C was the number of comparison (in our case $C = 6$). In effect, all p values from individual t-tests were multiplied by 6.

Statistical differences in radiative temperature (measured by thermographic camera) between the willow stands and the peaty meadow were evaluated using Student's paired t-test for dependent samples. The statistical differences between daily courses of the Bowen ratio in experimental stands were evaluated using the

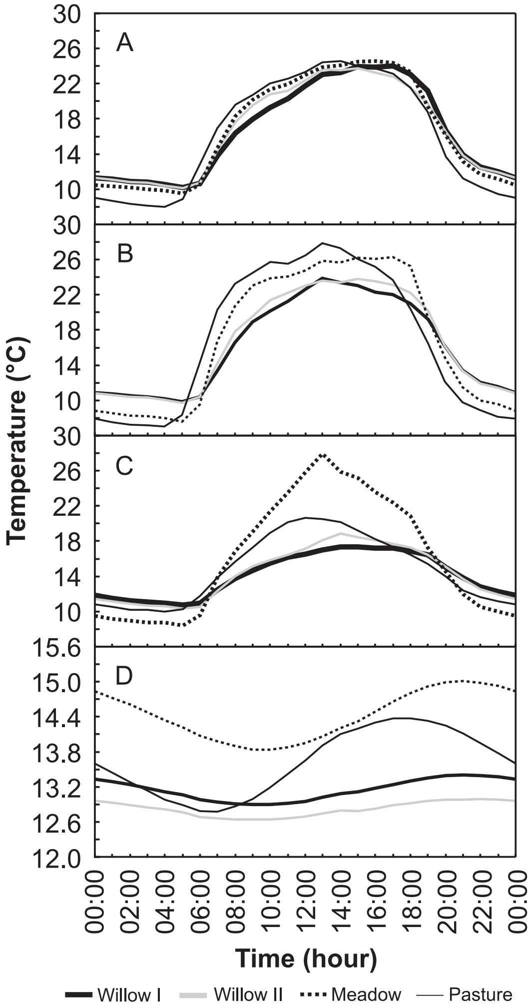

Fig. 1. Hourly mean temperatures at (**A**) 1.5 m above the surface, (**B**) stand surface, (**C**) soil surface, and (**D**) 0.15 m below the soil surface calculated for 39 days of measurement (7 June to 15 July 2002). Time series for four stands — two willow stands, a peaty meadow and a drained pasture — are shown.

pair *t*-test as well. The data were paired for the same time interval and the differences between all pairs were calculated and evaluated. The null hypothesis was: the pairs do not differ.

The relationship between relative air humidity and differences among temperatures between stands was evaluated with correlation analysis. The Lowess Smoothing local regression model (also sometimes referred to as Robust locally-weighted regression, StatSoft Inc. 2001) was used to evaluate the diurnal courses of the Bowen ratio.

Results

Temperature characteristics

A daily series of temperature measurements were made from 7 June to 15 July 2002 (Fig. 1 and Table 2). The smallest differences between individual stands in the temperature series were those measured at 1.5 m above the stands and at the stand surface ($p < 0.05$, $F = 2.71$, df = 3; and $p < 0.01$, $F = 4.77$, df = 3, respectively). The greatest differences between individual experimental stands in their temperature series were measured at the soil surface and at 0.15 m below soil surface ($p < 0.001$ in both cases, $F = 78.39$, df = 3; and $F = 279.0$, df = 3, respectively). The highest daily temperature amplitudes were measured at the stand surface of the peaty meadow and of the pasture.

The highest standard deviation (SD) and highest temperature amplitude at 1.5 m above the stand were found for the pasture, while the smallest ones were for the willow stand II. Similar results were found for the level at the stand surface. However, temperatures between stands at the soil surface were markedly different: in the meadow, the mean daily temperature amplitude was 22.9 °C with SD 7.7 °C, whereas in the willow stands the mean daily amplitudes were 7.9 and 9.8 °C with respective SDs of 2.7 and 3.6 °C. The daily pattern of temperature at the soil surface in the pasture was similar to that of the two willow stands. The widest amplitude of temperatures 0.15 m below the soil surface was recorded for the pasture (1.7 °C), the narrowest being found in the two willow stands (0.5 and 0.7 °C).

The comparison of standard deviations of daily temperature series and daily sums of precipitation showed that the temperature differences and the temperature amplitudes in all stands were more balanced with increasing relative humidity and during precipitation (Figs. 2 and 3). In contrast, 'drying' was associated with increase in temperature amplitudes — being slowest in the willow stands and fastest in the pasture.

We tested the relationship between the mean relative air humidity and the differences of mean stand surface temperature of the peaty meadow and willow stands from 8:30 to 18:30 (during

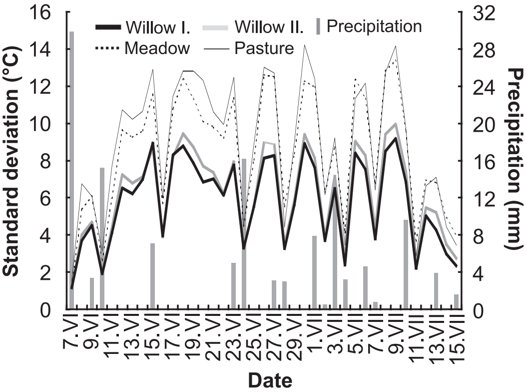

Fig. 2. Relationship between precipitation and stand surface daily temperature time series variation expressed as standard deviation. The lines indicate standard deviation of mean daily temperature, the columns indicate the amount of daily precipitation. A sudden decrease of temperature amplitudes after rain precipitation are obvious. Drying of stand is associated with an increase of daily temperature oscillation. The highest oscillation occurred in the pasture and in the peaty meadow, the lowest in the willow stands.

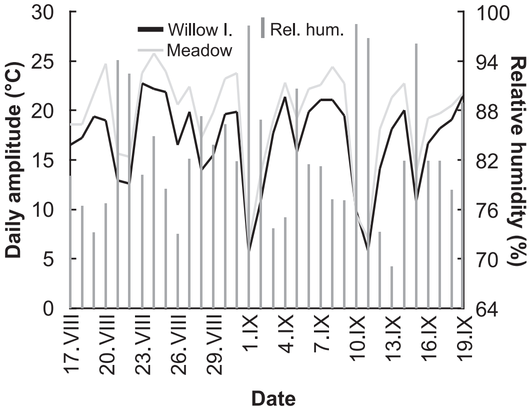

Fig. 3. Relationship between stand surface daily temperature amplitudes and daily means of relative air humidity. The lines indicate daily temperature amplitude time series, the columns indicate mean daily relative air humidity measured at 1.5 m above stand surface. The daily amplitudes increased with decreasing relative humidity. Decreasing daily temperature amplitude was in relation with increasing relative humidity of the air. Higher oscillation of daily temperature amplitudes was apparent in the peaty meadow.

Table 2. Daily mean temperatures and mean amplitudes of daily temperatures in vertical profiles of selected stands (± SD) for the time period between 7 June and 15 July 2002 and for selected sunny days only (13, 14, 15, 17, 18, 19, 20, 21, 23, 27 June and 5, 8, 9 July).

Vertical level & habitat	7 June–15 July 2002		Sunny days only	
	Mean temp. (°C)	Mean amplitude (°C)	Mean temp. (°C)	Mean amplitude (°C)
1.5 m above stand				
Willow I	16.74 ± 7.16	17.08 ± 5.41	19.82 ± 8.35	21.55 ± 2.52
Willow II	16.81 ± 7.17	16.48 ± 5.43	19.99 ± 8.34	21.12 ± 2.14
Peaty meadow	17.02 ± 7.68	18.73 ± 5.63	20.00 ± 9.24	23.43 ± 2.29
Pasture	16.37 ± 8.34	20.08 ± 6.79	18.95 ± 10.04	25.69 ± 3.07
Stand surface				
Willow I	16.38 ± 7.09	16.81 ± 5.57	19.36 ± 8.38	21.80 ± 2.37
Willow II	16.77 ± 7.53	17.58 ± 5.73	19.98 ± 8.86	22.52 ± 2.39
Peaty meadow	17.16 ± 9.50	24.02 ± 6.73	19.90 ± 11.60	29.45 ± 2.63
Pasture	17.11 ± 10.17	25.47 ± 8.36	20.03 ± 12.32	32.20 ± 2.43
Soil surface				
Willow I	14.14 ± 3.61	7.87 ± 2.73	15.28 ± 4.19	10.15 ± 1.46
Willow II	14.29 ± 4.17	9.80 ± 3.57	15.80 ± 4.98	13.32 ± 1.34
Peaty meadow	16.33 ± 8.24	22.94 ± 7.71	18.38 ± 10.30	29.93 ± 3.20
Pasture	14.83 ± 4.91	12.48 ± 4.38	15.84 ± 5.88	16.29 ± 1.78
–0.15 m below soil surface				
Willow I	13.15 ± 1.15	0.72 ± 0.31	13.31 ± 1.09	0.96 ± 0.20
Willow II	12.82 ± 0.87	0.53 ± 0.17	12.86 ± 0.79	0.60 ± 0.09
Peaty meadow	14.41 ± 1.66	1.52 ± 0.44	14.73 ± 1.64	1.86 ± 0.22
Pasture	13.60 ± 1.39	1.74 ± 0.64	13.90 ± 1.42	2.28 ± 0.29

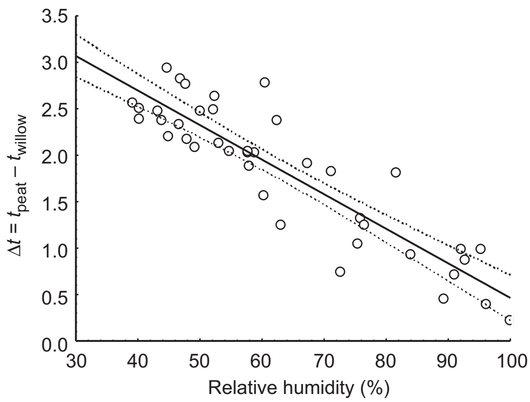

Fig. 4. Dependence of difference (Δt) of mean diurnal stand surface temperatures of the peaty meadow (t_{peat}) and the willow stand (t_{willow}) on mean relative humidity of the air (simple linear regression: $y = -0.0338x + 4.04$, $r = -0.889$, $r^2 = 0.791$, $p < 0.05$). Mean diurnal data were computed from 15 minute records of temperature and relative humidity. From 17 August to 19 September 2002 only data from 8:30 to 18:30 were used. The 95% confidence interval of the regression is shown.

this time interval we supposed that the weather conditions were unstable) for 35 days. The comparison showed a very close negative correlation between the relative humidity and the temperatures differences (simple linear regression: $r = -0.889$, $r^2 = 0.791$, $p < 0.05$, $n = 35$; *see* Fig. 4). With increasing differences of mean stand surface temperatures for this period oscillations in temperature increased (expressed as standard deviation (simple linear regression): $r = 0.914$, $r^2 = 0.835$, $p < 0.05$, $n = 35$).

Temperature amplitudes on sunny days

Mean daily temperatures and daily temperature amplitudes for individual stands on selected sunny days are given in Table 2. Mean temperatures at 1.5 m above the stand surface were similar for all four stands, though slightly higher above the pasture and lowest for both the willow stands. At the stand surface the widest temperature amplitude (32.2 °C) and highest mean temperature (20.0 °C) were recorded in the pasture, whereas a narrow temperature amplitude (21.8 and 22.5 °C) and low mean temperatures (19.4 and 20.0 °C) during the sunny days were recorded in both the willow stands.

The soil surface was mostly overheated in the peaty meadow, which showed as well a very high mean daily temperature amplitude (29.9 °C) in comparison with the other stands. As expected, temperature amplitudes below the soil surface were smallest in the two willow stands (1.0 and 0.6 °C) and largest in the pasture (2.3 °C).

To illustrate the temperature distribution at the surface of the experimental stands, a thermographic camera was used. The infrared (IR) pictures taken in the afternoon hours showed both lower temperatures and narrower temperature amplitudes in the willow stands as compared with those in the peaty meadow (Fig. 5).

The thermographic camera makes it possible to measure and plot 240 × 320 temperature pixels per picture. In order to compare temperatures between the willow stand and peaty meadow, temperatures measured in the studied areas (stands) were plotted in the form of lines. Each line contains 320 temperature pixels. During sunny weather temperatures measured in the willow stands were lower than the temperatures measured in the peaty meadow ($t = -8.49$, df = 8, $p < 0.05$; Fig. 5). The variability of temperatures was higher in the peaty meadow. Willow shrubs were apparently colder than their surrounding (Fig. 5A).

Bowen ratio

Bowen ratio (Eq. 1) was used as a simple parameter for evaluation and comparison of the latent and sensible heat distribution in the stands (Figs. 6 and 7). The Bowen ratio was lowest in both stands in the early morning (with the highest SD), when some of the values were even negative. These resulted from the definition and calculation of the Bowen ratio (Eq. 1).

In the willow stand the Bowen ratio increased after midday and SD values became smaller. In the peaty meadow, however, mean values did not change markedly during the day and SD values were higher than in the willow stand. At about 14:00, the Bowen ratio started to fall in the willow stand while SD values increased. Between 15:00 and 18:00, the Bowen ratio approached 1 in both stands. During the night, Bowen ratio values were comparable (about 0.8) in both stands and

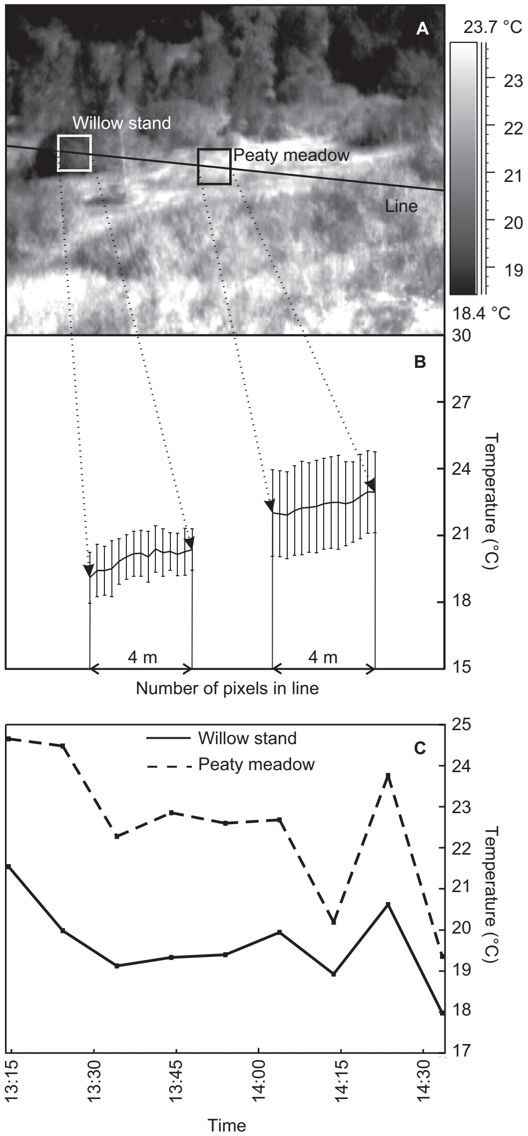

Fig. 5. Temperatures in the willow and peaty meadow stands (Horský potok floodplain) measured with a thermographic camera on 28 August 2002. — **A**: Infra-red picture was taken at 13:34 h. The grey scale indicates the range of temperatures. — **B**: Mean temperatures ±2 SD were determined from the infra-red pictures taken at 10-minute intervals from 13:15 to 14:35. The values of ±2 SD lie on the curve at 2-pixel intervals. — **C**: Temperatures between 13:15 and 14:35 in the willow stand and peaty meadow (t = –8.49, df = 8, p < 0.05). Each plotted value was calculated from all temperature pixels within marked square (841 pixels for each square = circa 16 m²).

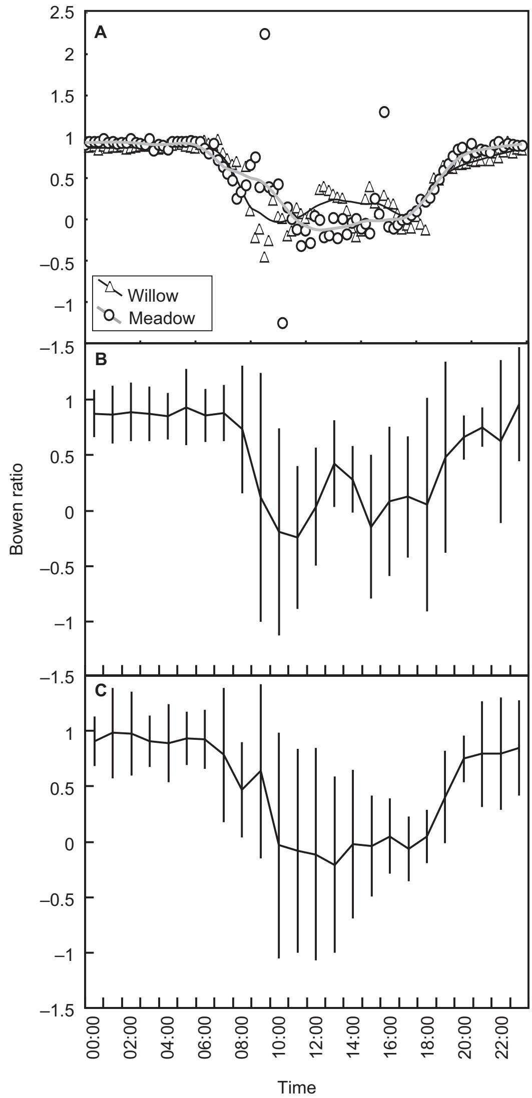

Fig. 6. The mean values of the Bowen ratio (dimensionless) from 17 August to 19 September 2002 plotted for 15 minutes and 1 hour interval. — **A**: The mean daily values of the Bowen ratio in 15-minute intervals, and the evolution of Bowen ratio values during the day (Lowess Smoothing function). The difference between the willow stand and the peaty meadow is significant (t = –0.86, df = 95, p < 0.05). — **B** and **C**: The variability of daily course of the Bowen ratio in 1 hour interval. Hourly means of the Bowen ratio ±2 SD in (**B**) the willow stand and (**C**) peaty meadow.

temperature variation was least. The mean Bowen ratio values were similar in both stands: 0.47 in the willow stand and 0.48 in the peaty meadow (t = –0.86, df = 95, p > 0.05).

During a sunny day, the Bowen ratio decreased from early morning to midday, i.e. the proportion of solar energy converted into latent

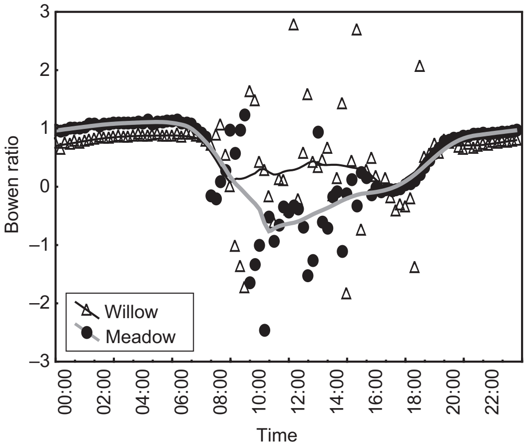

Fig. 7. Daily pattern of Bowen ratio values (dimensionless) in the willow stand and the peaty meadow during a sunny day (4 September 2002). Plotted are the 15 minute values of the Bowen ratio and the evolution of Bowen ratio values during the day (Lowess Smoothing function). The diference between the willow standand the peaty meadow is insignificant (t = 1.127, df = 95, p < 0.21).

heat increased (Fig. 7). The Lowess Smoothing plot showed that in the peaty meadow the Bowen ratio decreased to its minimum between 10:00 and 12:00 and then later increased towards late afternoon.

In the willow stand, the Bowen ratio decreased in the morning hours, but values again rose from around 9:00 to the afternoon. In the willow stand, the proportion of sensible heat increased during midday, which was perhaps due to a midday depression of transpiration. The Bowen ratio fluctuated more in the willow stand in the morning and evening hours, presumably as a result of the advection of air around the spherical willow shrub.

Discussion

Natural self-structured vegetation always approaches its most effective energy dissipation via a short-circuited atmospheric water cycle and thus minimises local diurnal temperature oscillations (Ripl and Wolter 2002). The pattern of temperature throughout the day, as well as vertical temperature profiles, can be used as indicators of a functional short water cycle and the functioning of different biotopes in the process of dissipating incoming solar energy (Hildmann 1999, Ripl *et al*. 2004).

Our results show similar daily temperature patterns 1.5 m above the willow stands and peaty meadow compared with the pasture. We assume a similar overlapping footprint for these wetland stands and similar spectral features for these types of vegetation cover, which results in a similar warming of the vegetation, mass flow and turbulent movement of air (not measured). Differences in temperature values measured in the pasture might be associated with a different form of air movement, catabatic flow and manner of surface heating/warming caused by the relative lack of water around the plants.

Wide temperature fluctuations at the vegetation surface and 0.15 m below the soil surface are mostly caused and influenced by the density and mass of the vegetation and by the structure and amount of detritus covering the soil surface. In the willow stand, the soil surface is covered by a dense and intensely-transpiring shrubby vegetation. Unlike the willow stand, in the peaty meadow fresh detritus and new peat are being formed. With a decreasing groundwater table in the soil horizon, thermal conductivity decreases as well (Přibáň *et al*. 1992, Geiger *et al*. 2003). So, the thin upper soil layer can become overheated and surface temperatures rise, the detritus of the peaty meadow acting as thermal insulation (Geiger *et al*. 2003). High soil surface temperatures can also be caused by a short vegetation cover and its low biomass. Similar patterns of temperature behaviour were recorded by Hojdová *et al*. (2005) in a peat bog.

Soil in the pasture is mostly formed of an acid brown soil (cambisol), which has a higher thermal conductivity than that of peat. The pasture becomes overheated because of its low evapotranspiration resulting from the lack of water in the soil or from the inability of the vegetation to maintain unlimited transpiration (Larcher 1995).

A comparison between the standard deviation of daily temperature measurements and daily sums of precipitation shows the moderation of temperatures at all sites and all vertical profile levels during rain. The difference of average surface temperatures in the peaty meadow and willow stand and relative air humidity shows a narrow negative correlation (r = –0.889), for 35 days averages of the time period between 08:30 to 18:30 (Fig. 4). These results show that with decreasing humidity the difference in surface temperatures at the observed sites rises and the temperature of the plant stand surface rises faster in the peaty meadow than in the willow stand. Together with the increasing difference of average surface temperatures between the stands, the variance of measured temperature values expressed as SD increases ($r = 0.914$, data not shown). This is indicative of the different behaviour of individual components of the vegetation mosaic in terms of their cooling effect driven by evapotranspiration. The time period (08:30–18:30) was selected in order to avoid nocturnal inversion and an unstable atmospheric boundary layer (Arya 2005) during which differences between the sites are obliterated. Dew apparently plays an important role as well.

The infrared thermograph provides information on the spatial distribution of temperatures: as, for example, the temperature mosaic of the wetland herb and shrub vegetation (Fig. 5). Temperature scanning in the IR spectrum with the thermographic camera showed that the surface temperature was lower and temperature fluctuations less in the willow stand than in the herbaceous vegetation. The results thus show the stabilizing effect of the willows on the temperature regime. Apart from meteorological conditions (air humidity, air turbulence, solar radiation), the vegetation's physiological control of transpiration plays an important role.

The Bowen ratio shows the relative ratio of sensible heat and latent heat fluxes; a ratio calculated from measured values of air temperature and air humidity. However, calculated ratios may be imprecise due to the measurements of air humidity being relatively inaccurate.

The presented results show that daily series of Bowen ratios in the willow stand and peaty meadow are similar during the night and early morning hours. Differences appear at about 11:00 when the Bowen ratio rises in the willow stand, i.e. the proportion of sensible heat here increases; in the afternoon hours, the Bowen ratio again decreases. The rise of the Bowen ratio during the midday can be interpreted as resulting from reduced transpiration, generally known as a 'midday depression' (Stocker 1956); the willow stand is unable to compensate for the water losses caused by intensive transpiration and the leaves close their stomata. Consequently, relatively more incident solar energy is converted to sensible heat. Subsequently, water gradually accumulates in the plant tissue, namely the leaf mesophyll, water deficit disappears, transpiration rate rises and Bowen ratio drops; for similar examples *see* Larcher (1995).

Negative values of the Bowen ratio indicate the substantial effect of advection in the stands studied here — warmer and drier air bringing additional energy into the stands. Linacre (1976) in this connection coined the term the 'oasis effect', which may act as a stress factor and an energy subsidy enhancing evapotranspiration.

Differences in the Bowen ratio for various types of stands equate with increases in air humidity, i.e. during dew or fog formation, and rain Bowen ratio values calculated from temperature and air humidity differences fluctuate chaotically, as they do during the night hours. In both cases, the Bowen ratio is no longer meaningful as no reliable differences in temperature and air humidity are obtained and no measurable flux of solar energy occurs.

Mean values of the Bowen ratio measured during this study are similar for both stands (~0.5 for the willow stand and peaty meadow). They practically do not differ from Bowen ratio values given for mires with a dense canopy (Kellner 2001), sedge wetland (Eaton *et al.* 2001) and bog (Valetiny *et al.* 2000). Bowen ratios for similar habitats in the Wet Meadows near Třeboň (Czech Republic) in a sedge-grass stand were lower than 0.2–0.3 (Přibáň and Ondok 1980), in a northern grasslands (eastern Siberia) they were about 0.2 (Yamazaki *et al.* 2004), etc.

Generally, moderated (or dampened) temperature series are detected particularly in wetlands and in areas with sufficient water for evapotranspiration with functioning vegetation (Přibáň *et al.* 1992, Królikowska *et al.* 1998, Bréda *et al.* 2006, Hais *et al* 2006). In this study, dampened oscillations of temperature with a small mean daily amplitude were recorded in willow stands. Similar results Jeník *et al.* (1984) described for stands of *Salix cinerea* L. In contrast, daily temperature amplitudes on the drained surfaces of a spoil heap without vegetation reached 60 °C on sunny cloudless days (temperate area — central Europe, Pecharová *et al.* 2001). Such results indicate the absence of a short-circuited atmospheric water cycle and ultimately the loss of the cooling capacity of the landscape.

An important aspect of energy-dissipative systems is their ability to close matter cycles within the given occupied space and thus minimise matter transport outside the system. The smallest parts or sub-units of an ecosystem which can couple energy dissipation and close matter cycles have been described as dissipative ecological units (DEU) by Ripl and Wolter (2002). The ability of the vegetation in a landscape to effectively control temperature amplitudes and how this relates to the minimisation of matter losses from catchments (of soluble cations with discharged water) has been well documented in this study area for three adjoining catchments (Procházka *et al.* 2001, Procházka *et al.* 2006). According to this energy and matter efficiency principle, such dissipative ecological unit systems can be considered functioning more naturally and more sustainably (Ripl and Wolter 2002). At the present time, more so than ever, all management measures (including landscape restoration projects) need greater holistic and functional understanding of natural systems. Temperature distribution can be one important criterion for evaluating a functioning landscape. Temperature distribution in the landscape and its relationship to the distribution of the vegetation can be effectively recorded by a thermographic camera.

In general, our results show that shrubs are more effective in temperature damping than herbaceous vegetation. We would suppose that more solar energy was dissipated as latent heat rather than converted to sensible heat in both wetland stands. Thus wetlands are important DEUs maintaining the landscape process of solar energy dissipation. The evaluation of temporal information concerning the course of daily temperatures and spatial information regarding temperature distribution in landscape units and the vegetation mosaic is one possible way of assessing vegetation functioning and understanding its role in solar energy dissipation.

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Appendix

Table I. The results of statistical analysis of the temperature measured between 7 June and 15 July 2002 at 1-h intervals in the vertical profile within the stands using one-way within-subject ANOVA. n.s. = not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

	All measurement days				Sunny days only			
Vertical level	*n*	df	Fisher's *F*	*p*	*n*	df	Fisher's *F*	*p*
1.5 m above stand	3744	3	2.71	*	1248	3	5.64	***
Stands surface	3744	3	4.12	**	1248	3	1.90	n.s.
Soil surface	3744	3	78.39	***	1248	3	85.56	***
0.15 m below soil surface	3744	3	279.00	***	1248	3	143.90	***

Table II. Comparison (paired *t*-test) of daily temperature series measured between 7 June and 15 July 2002 at 1-h intervals at all studied localities during all measurement days. *p* after Bonferroni correction. n.s. = not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

	1.5 m above stand			Stand surface		
	Willow II	Peaty meadow	Pasture	Willow II	Peaty meadow	Pasture
Willow I	n.s.	**	**	***	***	***
Willow II		*	***		**	n.s.
Peaty meadow			***			n.s.
	Soil surface			**0.15 m below soil surface**		
	Willow II	Peaty meadow	Pasture	Willow II	Peaty meadow	Pasture
Willow I	***	***	***	***	***	***
Willow II		***	***		***	***
Peaty meadow			***			***

Table III. Comparison (paired *t*-test) of daily temperature series measured between 7 June and 15 July 2002 at 1-h intervals in all studied localities during selected sunny days. *p* after Bonferroni correction. n.s. = not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

	1.5 m above stand			Stand surface		
	Willow II	Peaty meadow	Pasture	Willow II	Peaty meadow	Pasture
Willow I	n.s.	n.s.	***	***	n.s.	n.s.
Willow II		n.s.	***		n.s.	n.s.
Peaty meadow			***			n.s.
	Soil surface			**0.15 m below soil surface**		
	Willow II	Peaty meadow	Pasture	Willow II	Peaty meadow	Pasture
Willow I	***	***	**	***	***	***
Willow II		****	n.s.		***	***
Peaty meadow			***			***

Table IV. Temperature amplitudes measured between 7 June and 15 July 2002 at different height levels of the vertical profiles of the stands compared using one-way within-subject ANOVA. *** $p < 0.001$.

	All measurement days				Sunny days only			
Vertical level	*n*	df	Fisher's *F*	*p*	*n*	df	Fisher's *F*	*p*
1.5 m above stand	156	3	69.59	***	52	3	37.83	***
Stand surface	156	3	181.09	***	52	3	153.08	***
Soil surface	156	3	285.81	***	52	3	435.85	***
0.15 m below soil surface	156	3	165.20	***	52	3	435.08	***

Table V. Comparison (paired *t*-tests) of the daily temperature amplitudes at all localities at different heights of the vertical profiles in the stands for all measurement days. *p* after Bonferroni correction. n.s. = not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

	1.5 m above stand			Stand surface		
	Willow II	Peaty meadow	Pasture	Willow II	Peaty meadow	Pasture
Willow I	**	***	***	**	***	***
Willow II		***	***		***	***
Peaty meadow			**			n.s.
	Soil surface			**0.15 m below soil surface**		
	Willow II	Peaty meadow	Pasture	Willow II	Peaty meadow	Pasture
Willow I	***	***	***	**	***	***
Willow II		***	***		***	***
Peaty meadow			***			**

Table VI. Comparison (paired *t*-tests)) of the daily temperature amplitudes at all localities at different height levels of the vertical profiles in the stands for selected sunny days. *p* after Bonferroni correction. n.s. = not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

	1.5 m above stand			Stand surface		
	Willow II	Peaty meadow	Pasture	Willow II	Peaty meadow	Pasture
Willow I	n.s.	***	***	n.s.	***	***
Willow II		***	***		***	***
Peaty meadow			**			*
	Soil surface			**0.15 m below soil surface**		
	Willow II	Peaty meadow	Pasture	Willow II	Peaty meadow	Pasture
Willow I	***	***	***	***	***	***
Willow II		***	***		***	***
Peaty meadow			***			***