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Energy balance storage terms and big-leaf evapotranspiration in a mixed deciduous forest

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Abstract – Five different heat storage terms were studied in a mixed deciduous forest. All terms should be taken into account for the calculation of the overall heat storage, because they all can be significant during certain weather conditions and hours. Heat storage in biomass is estimated using surface temperatures measured with an infrared radiometer, which seems to be a good method. The often neglected photosynthetic heat storage may not be omitted. On a seasonal basis soil heat storage seems to be the most important term. The overall heat storage shows a small tendency for releasing heat to the atmosphere during fall. Fluctuations in overall heat storage are a result of complex changes of several climatic parameters. Due to the high degree of coupling of the forest to the atmosphere, accurate measurements of overall heat storage for the determination of big leaf forest evapotranspiration are not of the utmost importance.

energy storage / deciduous forest / evapotranspiration / infrared radiometer / coupling

Résumé – **Détermination des termes du bilan d’énergie et calcul de l’évapotranspiration par un modèle « big-leaf » en peuplement feuillu mélangé**. Cinq termes différents du bilan d’énergie ont été étudiés dans un peuplement feuillu mélangé. Etant donné que chacun de ces termes peut être significatif en fonction de l’heure et des conditions climatiques, ils doivent tous être pris en compte pour un calcul précis. L’énergie stockée dans la biomasse a été estimée à partir de la température de surface, mesurée à l’aide d’un radiomètre infrarouge. La méthode donne de bons résultats. Le stock d’énergie photosynthétique est non négligeable quoique souvent omis. Sur une base saisonnière, le stock d’énergie dans le sol est le terme le plus important. Lors de la chute des feuilles, on observe un flux positif d’énergie de l’écosystème vers l’atmosphère. Les variations du stock total d’énergie dans l’écosystème sont sous le contrôle d’un ensemble complexe de plusieurs paramètres climatiques. Cependant, étant donné le degré de couplage élevé entre la forêt et l’atmosphère, la mesure précise du stock total d’énergie dans l’écosystème n’est pas des plus importants pour le calcul de l’évapotranspiration par un modèle « big-leaf ».

stockage d’énergie / forêt feuillue / évapotranspiration / radiomètre infrarouge / couplage

1. INTRODUCTION

The evapotranspiration of vegetated surfaces can be estimated using the well-known Penman-Monteith equation [22]. By using this formula it can be seen that the evapotranspiration can be divided into two terms : (i) an equilibrium evapotranspiration term, and (ii) an imposed evapotranspiration rate [21]. While the latter term depends on the water vapour deficit of the air and the

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aerodynamic conditions, the former term is driven by the amount of available energy (A) for latent (λE) and sensible heat (H) processes.

The available energy is defined as the net radiation (R_n), from which the net change in energy storage within the canopy (S) is subtracted. Canopy storage S can be further subdivide into five terms [19]: soil heat storage (S_g), sensible heat storage in the canopy air (S_a), latent heat storage in the canopy air (S_w), biomass heat storage (S_v) and photosynthetic energy storage (S_p). Soil heat storage S_g can be further subdivided in the measured soil heat flux at depth z (G), and the soil heat storage to that depth ($S_g(z)$). In most studies S is simplified to G, while the other terms are considered to be negligible [31].

For ecosystems with a limited height and LAI this latter simplification is believed to be valid. However for densely vegetated ecosystems, especially forests, several authors have already shown that storage terms may not be neglected in the energy balances [18, 19, 34].

Sometimes S is also considered to be a fixed fraction of net radiation, or one or more components of S are thought to be negligible. One of the most commonly eliminated heat storage terms, due to its difficulty of determination, is the photosynthetic energy storage S_p [19].

Taking into consideration the different simplifications which are used when determining S the question arises what the influence of these simplifications is on the determination of big leaf forest evaporation. Aston [1, 2] pointed out that an accurate determination of the overall heat storage is of the utmost importance when determining forest evaporation using the Bowen ratio technique.

Energy balance studies have been conducted for several forest ecosystems. Examples of such work are available for temperate coniferous forest [e.g. 21, 34, 36, 37], for deciduous broadleaf and mixed forest [e.g. 18, 39], for tropical forest [e.g. 5, 25, 32] and subarctic forest [15].

This paper will first analyse the behaviour and magnitude of the different canopy storage terms (photosynthetic heat storage included) of a small mixed deciduous forest on an hourly, daily and seasonal basis, and examine their importance in respect to the net radiation. As suggested by Saxton and McCaughey [30] the biomass heat storage will be determined using surface temperatures measured with an infrared radiometer, instead of the commonly used thermocouples [1, 30]. Finally the influence of storage terms on the determination of forest evapotranspiration using the big-leaf approach will be determined.

2. MATERIALS AND METHODS

2.1. Calculation methods

The unit for all heat storage terms (equations 1–5) is W m^{-2}. A positive value for these terms indicates the transfer of energy to storage.

2.1.1. Latent and sensible heat storage

According to McCaughey and Saxton [19] the sensible S_a and latent S_w heat storage terms can be defined as

$$S_a = \int_0^{z_r} \rho C_p \left(\frac{\mathrm{d}T_a}{\mathrm{d}t}\right) \mathrm{d}z \tag{1}$$

$$S_w = \int_0^{z_r} \frac{\rho C_p}{\gamma} \left(\frac{\mathrm{d}e}{\mathrm{d}t}\right) \mathrm{d}z \tag{2}$$

where ρ is the air density (kg m^{-3}), C_p is the specific heat of air (1012 J kg^{-1} ^{o}C^{-1}), γ is the psychrometric constant (Pa ^{o}C^{-1}), e is the vapour pressure (Pa), T_a is the air temperature (^{o}C), z_r is the height of net radiation measurement (m) and t is time (s). Equations 1 and 2 are solved using the approximation suggested by Thom [38] and McCaughey and Saxton [19] which assumes that ρ and C_p are constant through the canopy layer. As representative air temperature the mean temperature measured at 4 heights in the canopy (1, 7.5, 14.6 and 21.6 m) is used, while e is a mean value determined from humidity measurements inside (at 1 m) and above (at 28 m) the canopy.

2.1.2. Soil heat storage

Soil heat storage S_g can be formulated, also according to McCaughey and Saxton [19], as

$$S_g = G + \int_0^{z} \rho_s C_s \left(\frac{\mathrm{d}T_s}{\mathrm{d}t}\right) \mathrm{d}z \tag{3}$$

where $\rho_s C_s$ is the specific heat for average moist soil (2.1 MJ m^{-3} ^{o}C^{-1}) [31], and T_s is the soil temperature (^{o}C). For G a mean value of both forest types (see later) is taken.

2.1.3. Heat storage in the vegetation

According to Thom [38] and McCaughey and Saxton [19] S_v can be written as

$$S_v = \int_0^{h_c} \rho_{\mathrm{veg}} C_{\mathrm{veg}} \left(\frac{\mathrm{d}T_v}{\mathrm{d}t}\right) \mathrm{d}z \tag{4}$$

where ρ_{veg} is the density of the vegetation (kg m^{-3} of column), C_{veg} is the specific heat of the vegetation (J kg^{-1} $^{\circ}$C^{-1}), T_v is the temperature of the biomass and h_c is the canopy height.

The solution of equation 4 assumes that a representative biomass temperature is measured, and in this research this was done using an infrared radiometer measuring the surface temperature of the canopy. It can be assumed that C_{veg} is roughly 70% of the value of the specific heat of water (thus 2930 J kg^{-1} $^{\circ}$C^{-1}), it can be deduced from equation 4 that [38]

$$S_v = 0.8 m_{\text{veg}} \delta T_v \tag{5}$$

where m_{veg}, the integral of ρ_{veg}dz from $z = 0$ to $z = h_c$, is the mass of vegetation over unit horizontal area (kg m^{-2}) and δT_v is the representative canopy temperature change in $^{\circ}$C per hour.

2.1.4. Photosynthetic heat capacity

The energy absorbed by biochemical processes S_p can be determined using the FORUG model [26, 27]. This model was used to estimate net photosynthesis for different upperstory and understory species in the mixed deciduous forest, hetero- and autotrophic soil respiration, and above-ground woody biomass respiration. The net amount of carbon fixed by the forest is converted to energy based on the fact that 1 g of CO_2 fixed yields 0.68 g DW [14], and average energy content for dry matter of woody plants is about 20 kJ g^{-1} DW [17].

2.1.5. Forest evapotranspiration

As mentioned before, the evapotranspiration of vegetated surfaces can be estimated using the well-known Penman-Monteith combination equation [22]

$$\lambda E = \frac{sA + \rho C_p / r_a \Delta e.}{s + \gamma (r_a + r_c) / r_a} \tag{6}$$

where E is evapotranspiration (kg m^{-2} s^{-1}) and λ the latent heat of evaporation (J kg^{-1}), s is the slope of the saturation vapour pressure curve at the air temperature (hPa $^{\circ}$C^{-1}), γ is the psychrometric constant (hPa $^{\circ}$C^{-1}), Δe is the vapour pressure deficit of the air (hPa) and r_a and r_c respectively the aerodynamic resistance and the surface resistance, all expressed in s m^{-1}. If stability factors are neglected, r_a can be expressed as

$$r_a = \frac{\left[\ln\left(\frac{z-d}{z_0} \right) \right]^2}{k^2 u_z} \tag{7}$$

with z_0 the surface roughness length (m), d the zero place displacement (m), k the von Karman constant (0.41) and u_z the windspeed (m s^{-1}) at the reference height z (m). Deducted values for d and z_0 from measurements above the canopy are respectively 0.81 h (own, unpublished results) and 0.1 h [6].

The surface resistance r_c can be determined using the approach of Stewart [33], based on work of Jarvis [12] for stomatal resistance, and further adapted by Ogink-Hendriks [24] for an oak forest in The Netherlands

$$g_c = g_{c,\max} (F_{\text{tot}}/F_{\max}) \, f(R_s) \, f(\Delta\rho_v) \, f(T_a) \, f(\theta) \tag{8}$$

with g_c, the surface conductance (m s^{-1}), being the inverse of r_c, g_c,max is a maximum surface conductance (m s^{-1}), F_{tot} the LAI at a the considered moment of the growing season (m^2 m^{-2}), $F_{\max}$ the maximal LAI (here 5 m^2 m^{-2} for the total forest), $f(R_s)$ is a global radiation function, $f(\Delta\rho_v)$ is a specific humidity deficit function, $f(T_a)$ is an air temperature function and $f(\theta)$ is a soil moisture deficit function. All functions yield a value between 0 and 1, as they express a reduction with respect to the maximum surface conductance, and are described by Ogink-Hendriks [24] as follows

$$f(R_s) = \frac{1254.1 R_s}{1000(R_s + 254.1)} \tag{9}$$

$$f(T_a) = \frac{T_a (40 - T_a)^{1.382}}{1295.43} \tag{10}$$

$$f(\theta) = 1 - \exp[0.0876(\Delta\theta - 141.9)] \tag{11}$$

$$f(\Delta\rho_v) = 0.2305 + 0.7695 \, 0.7089^{\Delta\rho_v} \tag{12}$$

where R_s, T_a, θ and $\Delta\rho_v$ are respectively expressed in W m^{-2}, $^{\circ}$C, mm and g kg^{-1}. θ over the top 1.0 m of soil is calculated from tensiometer measurements at different depths and the pF-curves at these depths. The value of $g_{c,\max}$ (0.05209 m s^{-1}) is calculated from the value found by Ogink-Hendriks [24] taken into account the slightly higher LAI in our forest (5.0 vs. 4.9). During rain and when the leaves were wet, r_c was set to 0. During night r_c was given the value 2000 s m^{-1}.

From intensive measurements during the 1996 growing season (leaf litter collection and optical LAI-sensors), the following LAI evolution during the growing season is used : (i) budburst occurs at May 1, and from then on there is a linear increase in LAI until July 1 (this is comparable to what is observed by [24], but is somewhat later than what is observed by [9]), (ii) from this date on the LAI remains constant until September 15, (iii) LAI decreases linearly and becomes 0 at December 1.

2.2. Site description

The Aelmoeseneie forest is a mixed deciduous, more than 70 years old forest near Ghent, Belgium (50º58′ N, 3º49′ E). The mean elevation above sea level is 16 m. The forest consists of two main forest types, an oak-beech forest with *Quercus robur* L. and *Fagus sylvatica* L. as the most common species in the upper layer and *Sorbus aucuparia* L., *Corylus avellana* L. and *Frangula alnus* Mill. in the understory. The second forest type is an ash forest with *Fraxinus excelsior* L. as the most important representative of the upperstory layer, and *C. avellana* and regeneration of *Acer pseudo-platanus* L. as the most frequent understory species. The maximal LAI during the 1996 growing season amounted 5.52 and 4.53 for respectively the oak-beech and ash forest. The mean canopy height of both forest types is 27 m, and the total area is 28 ha.

On the boundary of the two forest types, a 35 m high scaffolding tower is erected. The tower is surrounded by oak, ash and beech, and the canopies of the two latter species can easily be reached from the tower. At each 7 m there is a working platform where climatic parameters are measured. Three of the working platforms are within the canopy layer (at 7, 14 and 21 m), and two platforms are above the canopy at 28 and 35 m. Accordingly, the canopy could be divided in four distinct layers. The understory layer between 0–4 m, the lower canopy layer between 4–11 m, a middle canopy layer from 11–18 m and an upper canopy layer from 18–27 m. If necessary, a fifth layer can be considered between 27–36 m, the latter height being the height were the radiation sensor is installed.

The basic soil layer of the forest exists out of tertiary clay-loam complexes of the Paniseliaan. In the Glacial Period of the quartair, a loamy layer covered the tertiary layer. Loam was mixed with the local sand, which caused a sandloamy covering of 50 to 100 cm depth. The oak-beech forest has a typical thin quaternary layer of sand loam with a spotted texture B horizon on a shallow impermeable clay and sand complex of tertiary origin. The humus layer is of a moder type. The ash forest type is a ground water dependent alluvial part where the impermeable layer ceases. The small humus layer is of a mull type, and previous year litter is already degraded before the start of the growing season.

The biomass, comprising leaves, branches and stems, of the oak-beech and the ash forest type are respectively 26.68 and 20.10 kg m^{-2} for the upperstory and 0.48 and 0.85 kg m^{-2} for the understory [10]. For the calculations a mean value of 24.06 kg m^{-2} was considered.

More information about the forest, the tower and the experimental set-up can be found in Samson et al. [29].

2.3. Measurement period

Energy balance storage terms and forest evapo-transpiration were intensively analysed during a period in August 1998 (15–23). This period was chosen because there were no technical problems measuring all the necessary parameters, and also because during this period LAI of the forest is maximal, thus representing good average conditions during the growing season. This period was characterised by some warm, dry summer days (August 15–20), and some cloudy, rainy days (August 21–23).

The seasonal evolution of the daily storage terms is analysed for the period August 15 – October 31. This period was characterised by intensive rain periods from August 21 – September 16 (143.5 mm), from October 6–14 (30.3 mm) and from October 22 until the end of the month (75.2 mm).

2.4. Instrumentation and data collection

Net Radiation (Q*7.1, REBS) is measured from the fifth platform, just as incoming and reflected shortwave solar radiation (GS2, Delta-T-Devices). Both sensors face southward, to avoid any shading effects of the tower. Soil heat flux is measured at both forest types with self calibrating soil heat flux sensors (01-SC, Hukseflux) installed 8 cm under the soil surface. To take the energy storage above these heat flux sensors into account, a Pt100 temperature sensor was installed at a depth of 4 cm above each soil heat flux sensor. At each platform, and also 1 m above soil surface (at both forest types) air temperature is measured with shielded (aluminium housing) Pt100 sensors. Relative humidity is measured at 28.6 m (platform 4) and at 1 m above soil surface using ventilated, shielded psychrometers (HP-PX-5M SN, Vector Instruments). Windspeed is measured using 4 cup-anemometers (AN1, delta-T-Devices) installed at several heights above the canopy (37.0, 32.7, 30.6, 28.6 m). Free field precipitation is measured using a tipping-bucket raingauge (RG1, Delta-T-Devices) installed on the highest platform, and leaf wetness sensors (EE 507-264/SW120D345, ELE) are installed at two heights in the canopy (14.6 and 21.6 m) to monitor the surface wetness status of the leaves. Soil water potential is measured in both forest types using tensiometers (SWT6, Delta-T-Devices) installed at 6 depths (10, 25, 50, 100 and 150 cm).

Surface temperature was measured using an infrared radiometer (KT15, Heimann, wavelength sensitivity 8–14 µm) with a field of view (FOV) of 34°. The instrument was installed more or less 2m above the canopy, and was orientated East with a zenith angle of 65° [see 28].

All parameters are measured every 10 s, and a mean or cumulative value (depending on the parameter) is registered on a datalogger (HP 75000 and HP 34970, HP) every 10 minutes.

3. RESULTS AND DISCUSSION

3.1. Diurnal behaviour of storage components

In conformity with McCaughey and Saxton [19] three distinct weather conditions were chosen to characterise the diurnal behaviour of storage components. The selected conditions were: (i) clear sky and dry canopy (August 16); (ii) variable cloud and dry canopy (August 18); and (iii) variable cloud and wet canopy (August 22). During this last day rainfall was 6.7 mm (between 15 and 17 h). The hourly patterns of net radiation and of the different storage components for the three sample days are illustrated in *figures 1* and *2* respectively.

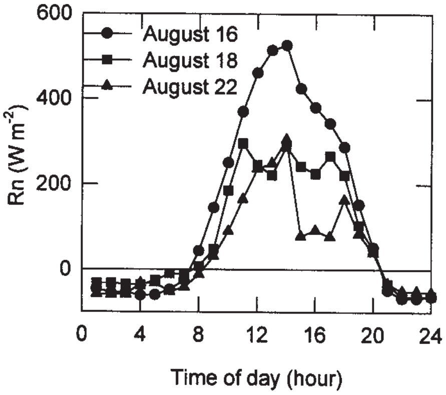

Figure 1. Diurnal pattern of net radiation (R_n) for August 16 (clear-sky conditions), August 18 (overcast conditions) and August 22 (variable cloud and rain).

Sensible heat storage (*figure 2a*) in the canopy air followed patterns similar to those found by other authors [18, 19, 23]. Also our values corresponded extremely well with the findings of these authors. For August 16 and August 18 the increase in S_a was initiated at sunrise. Peak values occurred at 10.00, 11.00 and 12.00 h for respectively the sunny, cloudy and rainy day. Throughout the rest of the day S_a decreased, until sensible heat was released to the atmosphere around 16.00 h. Nighttime values of S_a were negative. The amplitude of the sensible heat storage was highest for the sunny day, due to important solar radiation during daytime, and significant longwave radiation losses to the atmosphere during night. The rate of temperature change of the air was very similar as well above the canopy as for the four distinct levels in the canopy (figure not shown). However, the amplitude of the change in air temperature was most pronounced for the highest canopy level and the slightest change was observed at ground level, which partially illustrates the specific microclimate occurring in forest ecosystems.

In contrast to the other storage components, S_w (*figure 2b*) was characterised by irregular patterns also reported by other authors [16, 19]. For all weather conditions the sign of the flux varied around the zero line. The highest amplitude was found on the rainy day, due to evaporation of intercepted rain. Rain on August 22 was followed by an increase in windspeed which replaced the almost saturated air with dry air, and caused a sharp decrease in S_w. The hourly change in water vapour pressure in and above the canopy (data not shown) was highly variable and different for both heights, illustrating the specific microclimate occurring in forest ecosystems, and thus the necessity of measuring the relative humidity as well above as in the canopy.

A clear diurnal course was observed for the soil heat storage (*figure 2c*). The onset of S_g was a little delayed compared to sunrise. Heat storage increased till a plateau was reached, which existed throughout most of the day. Negative S_g values were reached somewhat later than for S_a. The observation of McCaughey and Saxton [19] that the S_g is usually the largest flux on an hourly basis, was not valid in this forest.

In the two forest types a different diurnal pattern of S_g was observed (*figure 3*). In the ash forest a pattern similar to that described by McCaughey and Saxton [19] was found back for the sunny day (August 16). The hourly values of S_g in this ash forest easily reached 100 W m^{-2}, which can be explained by the absence of an important humus layer and the lower LAI in the ash stand, inducing

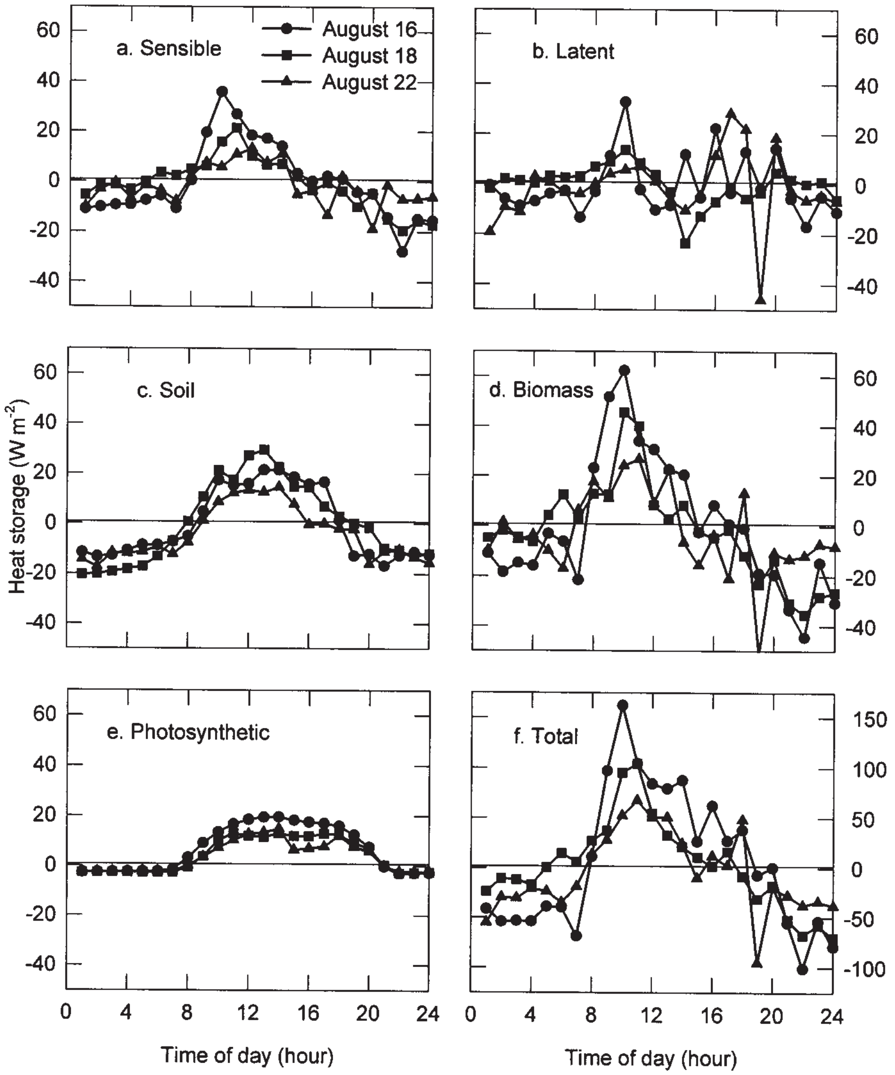

Figure 2. Diurnal pattern of: (a) sensible heat storage in the canopy layer; (b) latent heat storage in the canopy layer; (c) soil heat flux; (d) heat storage in the biomass; (e) heat stored by net photosynthesis; and (f) the overall heat storage. The sample days are August 16 (clear-sky conditions), August 18 (overcast conditions) and August 22 (variable cloud and rain).

more sun flecks at the soil surface. Due to a significant humus layer in the oak-beech forest (several centimeters) the amplitude of S_g is very small, and more independent of the weather type. On August 22 (low radiation and rain) the amplitude in the ash forest was similar to the pattern observed in the oak-beech forest. The presence of a humus layer and the LAI seems thus to be very important factors affecting the soil heat storage in forest ecosystems.

Heat storage in the biomass (*figure 2d*) was characterised by a comparable pattern as observed for S_a. S_v became positive around sunrise, reached a peak around 10.00 h for the dry days and around 11.00 h for the wet day. Afterwards, S_v dropped considerably, became negative at 15.00 h and then fluctuated between low positive or negative values. The increase and decrease in S_v was slightly in advance of S_a, indicating a quick heating up and cooling down of the canopy. The pattern observed

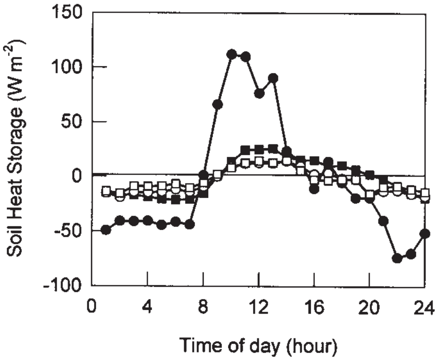

Figure 3. The diurnal pattern of the soil heat storage for the ash (circles) and oak-beech (squares) forest type. The sample days are August 16 (clear sky conditions) (closed symbols) and August 22 (variable cloud and rain) (open symbols).

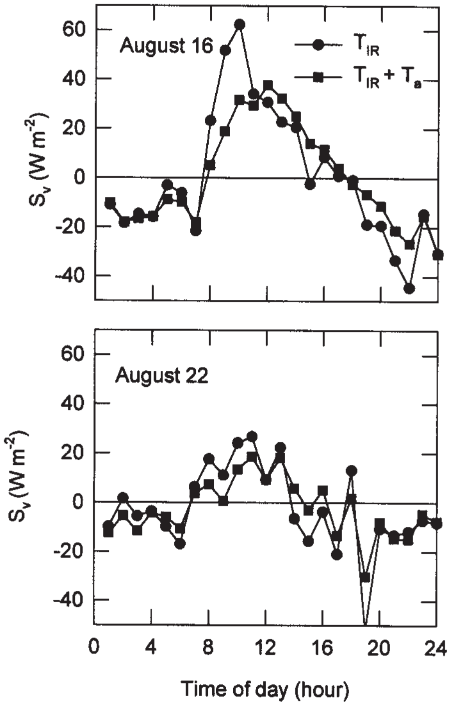

Figure 4. The diurnal pattern of heat storage in the biomass (S_v), calculated based on equation 5 where : (i) T_v is measured using an infrared radiometer (T_{IR}), or (ii) assuming that only the temperature of the upper part of the biomass is represented by the measured surface temperature, and the temperature of the lower stems equals air temperature, taking a lag of 2 hours into account ($T_{IR} + T_a$).

here is different from S_v estimated by McCaughey and Saxton [19], and discussed in detail by Saxton and McCaughey [30]. This difference can be explained by the different methods used. The above mentioned authors used thermocouples to measure the temperature of representative trees (different species, different heights and different depths in the stem) and shrubs. These authors found that the temperature change of stems was characterised by its lag in time of response in comparison to that of the air. Aston [1] measured, besides the temperature of twigs, branches and stems, also leaf temperature by use of thermocouples and noticed a different thermal response of leaves (i.e. absence of the lag in thermal response) compared to trunks. The different pattern of S_v observed in this research can be explained by the fact that the measured re-emitted long-wave radiation by the canopy is besides the contribution of stems and branches mainly due to the thermal behaviour of the leaves, which explains why the lag in time is not observed. Stockfors [35] mentions that there is a larger temperature amplitude in the upper parts of the stem, and thus also the branches, compared to the lower, more shaded parts of the stems. So, assuming that only the temperature of the upper part of the biomass was represented by the measured surface temperature, and the temperature of the lower stems equalled air temperature, taking a lag of two hours [30] into account, S_v was recalculated (*figure 4*). This assumption only had an impact on S_v on the sunny day (lower amplitude and a small phase shift), but on the cloudy and rainy day the impact was much less. Moreover, the obtained diurnal pattern for both days (*figure 4*) resembled largely the diurnal course calculated when S_v was only based on surface temperature. So, the suggestion made by Saxton and McCaughey [30] that the temperature change of tree tops and the upper canopy might be measured by an infrared radiometer, and used to calculate S_v seems to be valid. Because the upper part of the canopy is the major contributor to H_2O and CO_2 exchange processes (non-published FORUG-simulation results), and because the measurement of biomass storage is logistically difficult [19], especially in mixed forests, assuming that surface temperature represents canopy temperature might yield a good estimation of heat storage in the vegetation, although more research is needed to confirm this statement.

The heat stored by net carbon assimilation is illustrated in *figure 2e*, and corresponds well with values found by other authors [3, 4]. A clear diurnal course was observed. Differences in pattern and magnitude for the considered days were attributed to differences in radiation and temperature. During night there is a small constant release of energy to the ecosystem due to respiration. To estimate the photosynthetic heat storage also micrometeorological CO_2 flux measurements can be used to estimate S_p on the condition that also the storage of CO_2 in the canopy is measured. The photosynthetic heat storage is mostly denied in energy balance studies [19] or is often found to be negligible in size in comparison to R_n [38]. Jarvis et al. [12] suggested that the average photosynthetic flux during the day for coniferous forests is about 3% of R_n, but that it may reach much higher fractions in the early morning and evening. However, for the three selected days a mean daytime value of 6.1% of R_n was calculated in this study. Maximum and minimum values were respectively 14.8% (cloudy day) and 3.7% (sunny day) of R_n. Daytime values were in the same order of magnitude as for S_a, S_g and S_w. Also, during nighttime values were not negligible (mean nighttime value of 6.3% of R_n).

The diurnal pattern for the total heat storage (*figure 2f*) was comparable to those of S_a and S_v. Values also agree well with results found by McCaughey [18] and McCaughey and Saxton [19], somewhat smaller values were observed by Stewart and Thom [34] for a pine forest. The highest amplitude was noticed on the sunny day, the lowest on the cloudy/rainy day. During daytime values can be as high as 160 W m^{-2} and during night as low as –100 W m^{-2}. If only S_g would be taken into account, as is sometimes done, than errors up to 150 W m^{-2} can occur, which clearly illustrates that the different components of the overall heat storage should be taken into account. Also McCaughey and Saxton [19] concluded that using S_g as the sole indicator of canopy storage is not recommended.

The relative size of S with respect to R_n showed a high variability on an hourly basis. Early after sunset S sometimes exceeded R_n, resulting in a positive energy term available for sensible and latent heat exchange. Later during night S dropped to 40–50% of R_n, but under certain conditions it compensated R_n throughout almost the entire night. At sunset and sunrise, when R_n was small and changed from negative to positive values, or vice versa, S varied between more than –200% to more than 100% of R_n. During the morning S was at least around 30% of R_n but S decreased to less than 10% as R_n increased.

3.2. Daily and daytime pattern of heat storage

The daily and daytime totals of the five considered storage terms and the total storage are shown in *tables I and II*, for the considered measurement period (August 15–23). Daytime is defined as the period with positive R_n values. It is important to remark that during the measureonstrated by a significant change in mean air temperature [19]) (*table I*), which affects different storage components, particularly S_w [19].

Table I illustrates that on a daily basis the largest net amount of heat was stored by the photosynthetic process, and thus that S_p should always be taken into account. Other storage terms were close to zero, indicating there was no net gain or loss of energy to the system. The net loss of energy out of the soil compartment is remarkable, but can be explained by the fact that the preceding period was rather warm, resulting in a gain of energy, a part of

Table I. Summary of daily totals of the different storage terms (S_a the sensible heat storage, S_w the latent heat storage, S_g the soil heat storage, S_v the biomass heat storage, S_p the photosynthetic heat storage), the overall storage (S) and net radiation (R_n) (all expressed in MJ m^{-2} day^{-1}), together with values of daily mean air temperature (T_a) (°C) and precipitation (P) (mm) for the period August 15–23.

	S_a	S_w	S_g	S_v	S_p	S	R_n	T_a	P
August 15	–0.125	–0.188	–0.018	–0.225	0.532	–0.024	11.617	22.6	
August 16	–0.017	–0.027	–0.131	0.005	0.588	0.419	12.108	22.1	
August 17	0.023	0.018	0.035	0.046	0.482	0.604	10.685	21.7	
August 18	–0.071	–0.001	–0.011	–0.152	0.365	0.130	7.218	21.9	
August 19	0.014	–0.107	–0.142	0.032	0.446	0.243	9.735	21.2	
August 20	0.074	–0.063	–0.027	0.194	0.414	0.592	10.305	20.8	
August 21	–0.070	0.094	–0.042	–0.177	0.211	0.015	4.199	19.9	5.6
August 22	–0.141	–0.117	–0.342	–0.222	0.305	–0.516	3.899	18.1	6.7
August 23	0.210	0.289	0.201	0.440	0.178	1.318	3.258	17.5	21.7

Table II. Summary of daytime totals of the different storage terms (S_a the sensible heat storage, S_w the latent heat storage, S_g the soil heat storage, S_v the biomass heat storage, S_p the photosynthetic heat storage), the overall storage (S) and net radiation (R_n), all expressed in MJ m^{-2} day^{-1}, for the period August 15–23. Daytime is defined as the period with positive R_n values.

	S_a	S_w	S_g	S_v	S_p	S	R_n
August 15	0.098	0.070	0.346	0.168	0.628	1.309	13.097
August 16	0.381	0.192	0.474	0.574	0.676	2.296	14.241
August 17	0.282	0.118	0.547	0.444	0.570	1.963	12.684
August 18	0.135	–0.025	0.278	0.160	0.464	1.012	8.664
August 19	0.389	0.064	0.628	0.393	0.528	2.002	11.735
August 20	0.277	0.058	0.444	0.466	0.502	1.747	12.146
August 21	0.164	–0.057	0.257	0.148	0.259	0.772	5.012
August 22	0.118	0.036	0.172	0.049	0.371	0.747	5.818
August 23	0.147	0.215	0.380	0.315	0.259	1.316	4.717

which was again released when air temperature decreased. During the wet period (August 21–23) energy storage in water vapour became important.

McCaughey [18] stated that when canopy is dry and net radiation is high, the daily total storage seldom exceeds 2–3% of R_n, and thus can safely be ignored. Our research yielded more or less comparable results, for moderate R_n total storage ranged from –0.2 to 5.7% of R_n, with a mean value around 3.2%. However for cloudy days with rain or a drying canopy the comparative size of S can be much larger (40.5% on August 23) and also negative (–13.2% on August 22). So, it is safer to calculate the total energy storage for each day instead of ignoring it beforehand.

The contribution of the different storage terms to the overall storage during daytime is shown in *table II*. During the entire period, all terms, and consequently overall storage, were positive. The only exception, in accordance with findings of McCaughey and Saxton [19], was S_w, which also on hourly basis was the most variable term. The largest heat storage was due to the photosynthesis process, followed by heat storage in the soil and vegetation. The smallest values were observed for S_w. S was between 10.0 and 17.1% of R_n for the dry period, and varied between 12.8 and 27.9% for the wet period. Again it is clear that the day to day variability of S compared to R_n can be high.

3.2.1. Seasonal pattern of storage

The seasonal evolution of the daily heat storage from August 15 – October 31 is illustrated in *figure 5*. Only data from one psychrometer, installed above the canopy, could be used for calculating daily S_w values. Missing data of other parameters are due to technical, mainly datalogging, problems.

The daily sensible and latent heat storage (respectively *figures 5a* and *5b*) were, as found earlier, rather small, and there was no seasonal evolution for both storage terms. Just as found by McCaughey and Saxton [19], the soil heat storage term (*figure 5c*) was significantly larger than the other storage terms. Summing the daily values S_g was strongly negative during the considered period, indicating a net release of heat from the soil. The only term indicating a clear seasonal trend was the heat fixed by the photosynthesis process (*figure 5e*). This behaviour is not surprising as net photosynthesis decreases towards the end of the growing season [27]. Hence, during the growing season the positive contribution of S_p to the overall heat storage seems to be important, while at the beginning, at the end and out of the growing season its contribution becomes negligible. The total daily heat storage (*figure 5f*) fluctuated between 1.32 (day 235) and –2.20 (day 291) MJ m^{-2} day^{-1}. The ecosystem released heat, accumulated during the growing season, to the environment during fall (*figure 5f*).

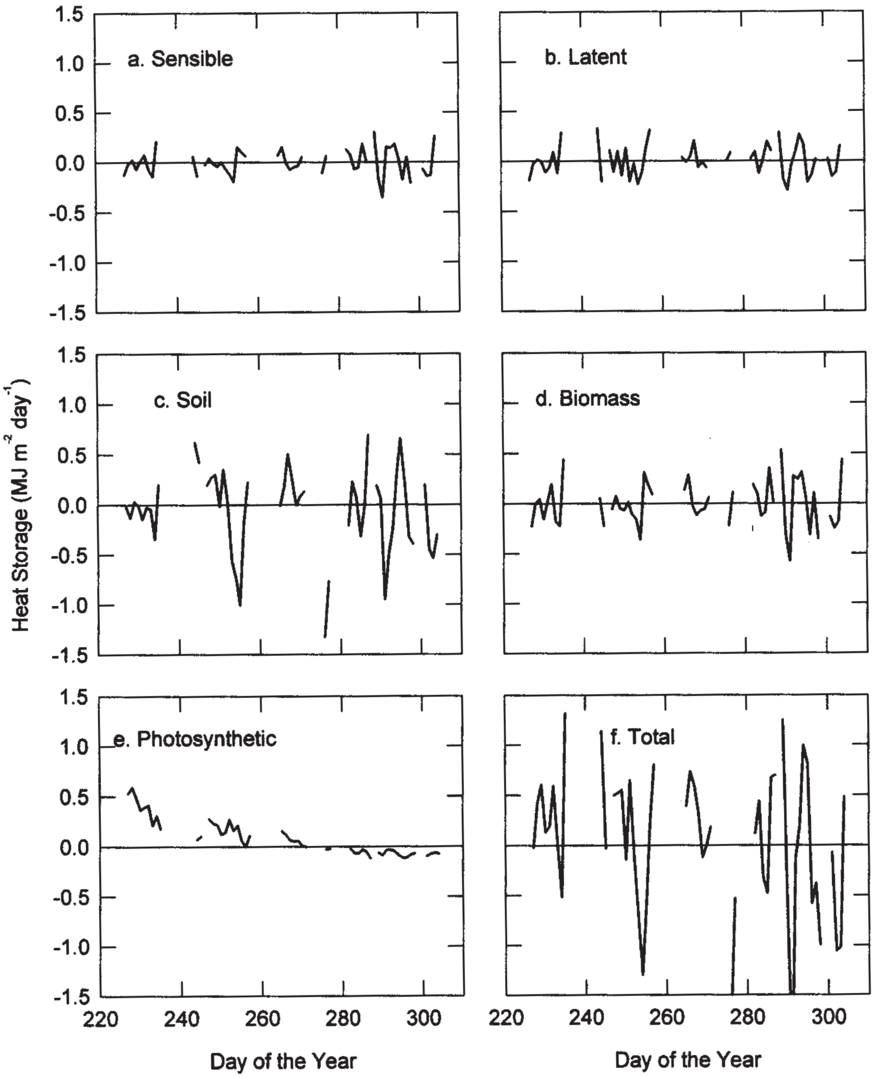

Figure 5. Seasonal patterns of daily totals of : (a) sensible heat storage in the canopy layer; (b) latent heat storage in the canopy layer; (c) soil heat flux; (d) biomass heat storage; (e) heat storage by net photosynthesis; and (f) overall heat storage. Day 220 is August 8 and Day 310 is November 6, 1998.

Large fluctuations in overall heat storage (*figure 5f*) can sometimes, but not always, be attributed to obvious changes in air mass. Examples of this phenomenon are the drops in air temperature (–3.7 °C) and windspeed (–2.5 m s^{-1}) between day 253 and 254 accompanied with a decrease in overall heat storage; a larger decrease in temperature (–5.4 °C) and windspeed (–4.7 m s^{-1}) is registered between day 290 and day 291, now with an even more pronounced release of energy as the result. On the other hand, air temperature (+3.5 °C) and windspeed (+4.2 m s^{-1}) suddenly increased between day 293 and day 294, with a rise in heat storage as the result. However, an obvious change in air mass is not always reflected in the overall heat storage, e.g. between day 286 and day 287 a clear increase in air temperature did not cause the expected increase in overall heat storage, which is explained by rain and cloudy weather conditions occurring during daytime period. Fluctuations in overall heat storage are thus a result of complex changes in different climatic parameters as air temperature, windspeed, radiation and the occurrence of rain.

As R_n decreased during the considered period, and as the ecosystem only showed a slight net tendency for releasing heat, the overall heat storage influenced more and more the available energy (R_n–S). On some days (e.g. day 289 and 294) all net radiation was stored in the canopy, while during other days (e.g. day 290 and 303) release of heat from the ecosystem was of the same magnitude or even larger than R_n.

3.2.3. Storage and big leaf evapotranspiration

Forest evapotranspiration was only calculated for the dry period (August 15–20). Two different approaches were used for taking the available energy to the ecosystem into account. First the storage term was considered to be 3% of R_n, which is a typical daily value when canopy is dry [18], in the second case the measured overall storage term was used. For August 16 and 18 the difference in storage approximation is given in *figure 6*. For these days the difference between both storage terms, with a peak value around 10.00–11.00 h up to 150 W m^{-2}, followed mainly the diurnal course of S because of the small value of $0.03*R_n$. The amplitude of the estimated difference between both storage terms was more pronounced for the sunny day (August 16).

In *figure 7* the diurnal course of latent heat exchange is shown for August 16 and 18, with S determined in two different ways as explained above. During night there was a negligible difference between both methods. After sunrise the difference increased, with the lowest latent heat exchange observed for the calculations based on measured heat storage, and peaked for both days at 10.00 h. Especially on the sunny day the maximal difference was rather large (>50 W m^{-2}), but was immediately followed by a very sharp decline. For the cloudy day there was during several morning hours a deviation of about 10 W m^{-2}, which was almost completely reduced to 0 around 15.00 h.

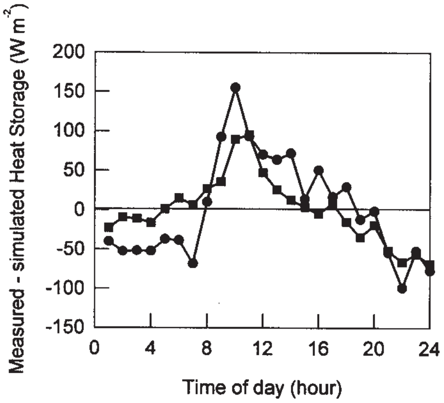

Figure 6. The diurnal pattern of the difference between measured and simulated (3% of R_n) overall heat storage. Sample days are August 16 (clear-sky conditions) (closed circles) and August 18 (overcast conditions) (closed squares).

The difference in daily evapotranspiration sum for the period August 15–20, calculated by the two described methods, was almost negligible (0.12 ± 0.08 mm day^{-1}), with the calculations based on measured heat storage resulting in a somewhat lower evapotranspiration (3.09 ± 0.33 mm day^{-1}). Extrapolating the mean daily difference in latent heat exchange to an entire growing season (May–September) resulted in a difference in evapotranspiration of only 18.48 mm.

The above mentioned observations, on one hand the rather large differences in S (*figure 6*), and on the other hand the small differences in latent heat exchange (*figure 7*), can be explained by the decoupling coefficient Ω [13]. The coupling (1 – Ω) between the forest “Aelmoeseneie” and the atmosphere was rather strong,

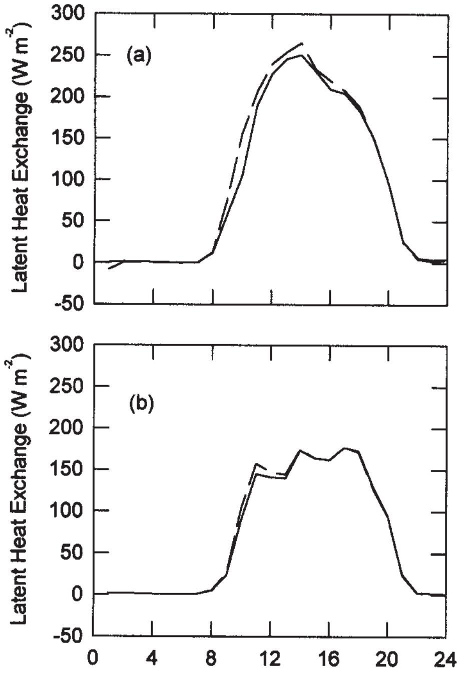

Figure 7. The diurnal patterns of latent heat exchange calculated using two different methods : (i) based on measured heat storage (solid line), and (ii) based on simulated heat storage (3% of R_n) (dashed line). The selected sample days are : (a) August 16 (clear-sky conditions); and (b) August 18 (overcast conditions).

and amounted on average 0.10 for the period August 15–20, which is within the range (0.05–0.2) observed by Granier et al. [7] for a beech forest. Similar values were also found for a beech forest in Germany [8, 9]. A high coupling decreases the importance of the available energy to the overall evapotranspiration.

For ecosystems strongly coupled to the atmosphere, the determination of the heat storage, and thus of the available energy, seems to be less crucial for the determination of latent heat exchange using the Penman-Monteith approach. For less coupled ecosystems (such as in greenhouses) an accurate determination of the heat storage, and more precisely of the available energy will be much more important. Also, if the Bowen-ratio technique is used for the calculation of latent heat exchange the exact hourly determination of the overall heat storage becomes much more important [1,2].

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