

# ENERGY BALANCE STORAGE TERMS IN A MATURE MIXED FOREST AT PETAWAWA, ONTARIO – A CASE STUDY

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**Abstract.** The energy storage terms for a mature mixed forest at Petawawa, Ontario are reported for 38 days in the summer of 1982 when the forest was in full leaf. Hourly, daily and daytime values of the storage terms are documented. The biomass storage term,  $Q_s$ , should be calculated from measurement of biomass temperature change. For hourly periods, the storage terms can be of significant size with respect to net radiation,  $Q^*$ . This is especially the case at night, in the early morning after sunrise, and near sunset. The importance of the storage terms is still pronounced when daytime totals are considered – the ratio of the total storage ( $Q_s$ ) to  $Q^*$  varied from 1 to 15% for the whole sample, but is typically between 5 and 10%. For daily totals when the canopy is dry and the net radiation high,  $Q_s$  is typically 2 to 3% of  $Q^*$ . However, it can be up to 10% of  $Q^*$  under particular conditions (overcast days, or during or immediately following rainfall).

## 1. Introduction

In the measurement of the energy balance of tall vegetation canopies, it is often assumed that the storage terms are negligible. In part, this may be the result of measurement considerations because some of the storage terms are difficult to estimate. This is especially the case with the biomass storage term which requires measurement of the biomass temperature change, as well as the mass of the vegetation. The latter requires detailed vegetation sampling. Tajchman (1971) evaluated heat storage in the biomass, soil and canopy air for a 70-yr old, Norway spruce, 27.2 m high canopy near Munich, West Germany. Total heat storage in the canopy was found to be small, and on cloudy days it “had no practical significance in energy balance calculations”. Stewart and Thom (1973) report values of the energy storage terms for Thetford Forest, a canopy composed of Scots and Corsican pine with a mean height of 15.8 m. The results from 7 fine days showed that hourly storage is an important term in the energy balance. For all days, total storage was positive in the morning after sunrise with a maximum value of around  $40 \text{ W m}^{-2}$ . It then had a downward trend toward zero at midday, remained close to zero in the early afternoon, became negative in the late afternoon, and reached a maximum negative value of around  $40 \text{ W m}^{-2}$  close to sunset. Munro (1979) reported total daytime storage values for the Beverly Swamp for five days in August and September 1977. Total daytime energy storage varied from 3 to 7% of  $Q^*$  for the mixed deciduous and cedar canopy at this site.

This paper reports measurements of the canopy and soil storage terms for the mature mixed forest at Petawawa, Ontario. A total of 38 days of data have been analyzed for three periods in the summer of 1982 when the trees were in full leaf. The sample periods were chosen to reflect times of both high soil moisture content and low soil moisture

content. Also, the difference between storage terms for a wet and dry canopy, as well as hourly, daily and daytime patterns of energy storage are described.

## 2. Calculation of Storage Terms

If one assumes the photosynthetic storage to be negligibly small, the overall storage ( $Q_s$ ) is given as

$$Q_s = Q_a + Q_w + Q_v + Q_g, \quad (1)$$

where  $Q_a$  is the sensible heat storage in the canopy air,  $Q_w$  is the latent heat storage in the same layer,  $Q_v$  is the heat storage in the vegetation, and  $Q_g$  is the storage rate in the soil, evaluated as the surface value of soil heat flux. All values are in  $\text{W m}^{-2}$ , and the convention of positive values signifying transfer of energy to storage is adopted. Formally, the terms on the r.h.s. of Equation (1) are found from

$$\left. \begin{aligned} Q_a &= \int_0^{z_r} \rho C_p \frac{dT}{dt} dz, \\ Q_w &= \int_0^{z_r} \frac{\rho C_p}{\gamma} \frac{de}{dt} dz, \\ Q_v &= \int_0^h \rho_{\text{veg}} C_{\text{veg}} \frac{dT_b}{dt} dz, \\ Q_g &= Q_{g(z)} + \int_0^z \rho_s C_s \frac{dT_s}{dt} dz, \end{aligned} \right\} \quad (2)$$

where  $\rho$  and  $\rho_s$  are air and soil density, respectively ( $\text{kg m}^{-3}$ ),  $\rho_{\text{veg}}$  is density of vegetation ( $\text{kg m}^{-3}$  of column),  $C_p$ ,  $C_s$ , and  $C_{\text{veg}}$  are the specific heats ( $\text{J kg}^{-1} \text{ }^\circ\text{C}^{-1}$ ) of air, soil, and vegetation respectively,  $\gamma$  is the psychrometric constant ( $\text{mbar } ^\circ\text{C}^{-1}$ ),  $e$  is vapour pressure (mbar),  $T$ ,  $T_b$ , and  $T_s$  are dry-bulb air temperature, biomass temperature, and soil temperature, respectively ( $^\circ\text{C}$ ),  $Q_{g(z)}$  is measured soil heat flux at depth  $z$ ,  $z_r$  is the height of net radiation measurement, and  $h$  is canopy height. It is quite reasonable to assume  $\rho$ ,  $\gamma$ , and  $C_p$  to be constant in the canopy layer, and following Thom (1975), the relations for the above-ground storage terms reduce to

$$\begin{aligned} Q_a &= 0.33z_r \delta T, \\ Q_w &= 0.5z_r \delta e, \\ Q_v &= 0.8m_{\text{veg}} \delta T_b, \end{aligned} \quad (3)$$

where  $m_{veg}$  is the mass of vegetation over unit horizontal area, and  $\delta T$ ,  $\delta T_b$ , and  $\delta e$  are hourly rates of change of air and biomass temperatures and of vapour pressure. The expression for  $Q_v$  assumes that the specific heat of vegetation is 70% that for water. It is necessary to evaluate  $\delta T$ ,  $\delta T_b$ , and  $\delta e$  from measurements at a 'representative' level in the canopy (Thom, 1975). In this experiment,  $\delta T$  is a mean value obtained from measurements taken at the base of the canopy, in the upper canopy zone, and above the canopy in the boundary layer.  $\delta e$  is obtained from measurements of vapour pressure at the base of the canopy and in the boundary layer above the canopy. Vapour pressure was not measured in the upper canopy zone. Ideally, the above-canopy level should be  $z_r$  (21.34 m); in this experiment, however, it was 23.5 m. This does not make a significant difference because the temperature gradients above the canopy are very small (McCaughey and Brintnell, 1984). As well, the rates of change of air temperature above the canopy and at 15.24 m height are almost identical (Figure 2).  $\delta T_b$  is evaluated from vertically integrated biomass temperature values from five sample points on each of two trees.

The surface soil heat flux reduces to

$$Q_g = Q_{g(z)} + \{(C_m X_m + C_o X_o + C_w X_w)/3600\} \delta T_s \delta z, \quad (4)$$

where  $C_m$ ,  $C_o$ , and  $C_w$  are the heat capacities ( $J m^{-3} ^\circ C^{-1}$ ) of mineral matter, organic matter, and water, respectively.  $X_m$ ,  $X_o$ , and  $X_w$  are the corresponding volume fractions,  $\delta T_s$  is the rate of change of soil temperature ( $^\circ C hr^{-1}$ ), and  $\delta z$  is the depth of soil from the surface to level  $z$ .  $X_m$  and  $X_o$  were determined from loss-on-ignition analysis of two soil samples (Brintnell, 1983), and average values of  $2 \times 10^6$  and  $2.5 \times 10^6 J m^{-3} ^\circ C^{-1}$  for  $C_m$  and  $C_o$  were assigned (De Vries, 1963).  $X_w$  was measured each day.

### 3. Experimental Site and Measurements

The study was conducted at the Petawawa National Forestry Institute (45° 58' N, 77° 25' W). The site is located in an extensive stand of mixed forest consisting of the following species and percent frequency estimates: white pine (*Pinus strobus* L.) (5%); red pine (*Pinus resinosa* Ait.) (1%); white spruce (*Picea glauca* (Moench) Voss) and black spruce (*Picea mariana* (Mill.) B.S.P.) (13%); balsam fir (*Abies balsamea* (L.) Mill.) (35%); red maple (*Acer rubrum* L.) (23%); red oak (*Quercus rubra* L.) (6%); yellow birch (*Betula alleghaniensis* Britton) (7%); shrubs, principally nannyberry (*Viburnum lentago* L.) (6%); dead trees (4%).

A detailed vegetation survey was performed in a 1050.7 m<sup>2</sup> sample area centred on the 39 m-high research tower. For each tree, the circumference and height were measured, the results being summarized in Table I. The overall density of the forest is 2664 stems ha<sup>-1</sup>, and the vegetation is distributed into three layers with mean tops of approximately 3 m for the lowest layer, 13 m for the middle one, and 19 m for the upper layer.

The soil in the area is a sandy loam over a gravelly glacial till. The surface layer (0–5 cm) is highly organic, being mainly coniferous needles and leaves. At a depth of

TABLE I

Summary of tree dimensions and forest density at Petawawa. The sample plot was circular, centered on the research tower, and 1050.7 m<sup>2</sup> in area.

Circumference (m)	0-0.1	0.11-0.2	0.21-0.60	0.61-1.0	> 1.0
Mean tree height (m)	1.97	4.78	11.03	14.64	19.27
Standard deviation (m)	0.50	1.90	3.46	4.05	1.69
Mean DBH (m) <sup>a</sup>	0.0143	0.0482	0.1164	0.2357	0.4478
Standard deviation (m)	0.0079	0.0090	0.0369	0.0320	0.0935
Number of stems in sample plot	134	43	64	18	11
Stems ha <sup>-1</sup>	1370 <sup>b</sup>	409	609	171	105

<sup>a</sup> DBH = diameter at breast height.

<sup>b</sup> Based upon 144 stems in sample plot. The height of ten trees in this group was not measured in the field.

5 cm, there is an ash layer approximately 5 mm thick which resulted from a forest fire that occurred about 50 yr ago. Below the ash layer down to a depth of about 15 cm, there is still evidence of a high fraction of organic matter and litter. From 15 to 17 cm, there is a dark loam with a high clay content. Below 27 cm the soil changes to light sandy loam with increasing numbers of stones with depth. At 40 cm, the frequency of stones increases dramatically. The maximum rooting depth of the trees is 42 cm.

The soil heat flux was measured at 5 cm with a Middleton flux plate (Type CN-3). Soil temperature was measured with a thermocouple at a depth of 2.5 cm directly over the plate. Wet- and dry-bulb air temperatures were measured with aspirated psychrometers at two levels: 3.05 and 23.5 m. Thermocouple probes (Omega Eng. Corp.) were used, and each pair was shielded and aspirated at 5.4 m s<sup>-1</sup> by 12 V Micronel fans (Model V361L). At 15.24 m, dry-bulb air temperature was measured with an un-aspirated, shielded, 36 a.w.g. thermocouple. The shield allowed free flow of air through it. We are satisfied that the use of the very small un-aspirated thermocouple gave representative air temperatures. Its performance was compared to an aspirated thermocouple probe prior to the experiment, and no significant differences were found. Furthermore, during the experiment, the small differences between the air temperatures at 15.24 m and those at 23.5 m, where an aspirated probe was used, were consistent with the magnitude of the measured temperature differences above the canopy. Biomass temperature was measured with a 10-junction parallel thermocouple. Each junction was encapsulated in a thin-walled aluminum tube, 15 cm long. Five of the junctions were inserted to a depth of 10 cm into a red maple tree at heights of 1.52, 3.05, 4.57, 6.1, and 7.62 m. The other five junctions were inserted into a white pine at heights of 2.13, 4.57, 7.01, 9.45, and 11.89 m. The biomass thermocouples were oriented toward the east. Also, every attempt was made to ensure that the projecting ends of the sensors were shaded from direct radiation by the surrounding branches. Given that a 10 cm length of each probe was embedded in the trees, it is unlikely that significant heat conduction occurred down the probe to the sensor. Furthermore, an examination of the data revealed no evidence of a more rapid rate of change of biomass temperature whenever the sensors faced the sun. Net radiation was measured at a height of 21.34 m by a

Middleton net pyrradiometer (Type CN-1), which was continuously purged by nitrogen. All signals were integrated and recorded hourly with a Campbell Scientific Data System (Type CR5). The volumetric soil moisture in the top 5 cm was determined by gravimetric analysis of two, 210 cc soil samples each day at 0900 LAT. Precipitation was measured with a tipping bucket gauge (Sierra Mfg. Co.) on a cleared site, 4.5 km distant, and recorded on a Campbell Scientific Micrologger (Type CR21). Measurements were started on June 15 and continued until September 8.

By applying Whittaker and Woodwell's equations (1968) to the DBH data (Table I), the mass of vegetation over unit horizontal area for this forest,  $m_{veg}$ , was found to be  $23.05 \text{ kg m}^{-3}$ .

#### 4. Results and Discussion

The storage terms were evaluated for each hour for a total of 38 days: June 16 to 30, July 16 to 30, and August 7 to 14. In June, the soil moisture was high (20–35% by volume), whilst in July and August it was low for this area (8–25%). The high soil moisture in June was the result of frequent rain events, one of which was very high – 31 mm on June 19 (Figure 1). There was a clear drying cycle from July 16 to 26.

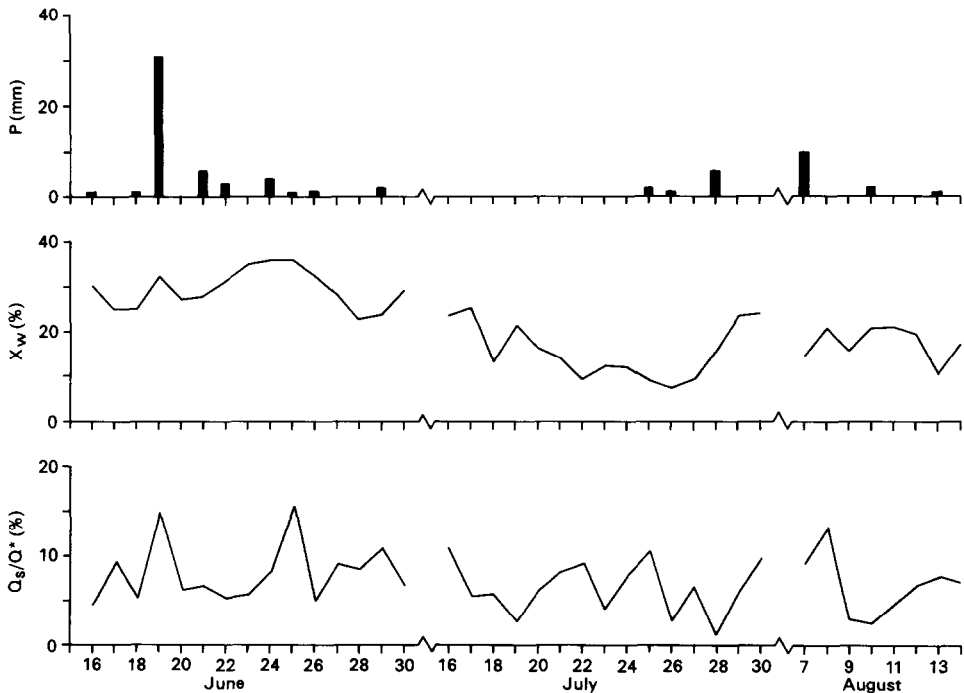


Fig. 1. Daytime totals of total heat storage ( $Q_s$ )/net radiation ( $Q^*$ ), daily volumetric soil moisture ( $X_w$ ), and precipitation ( $P$ ) at Petawawa, 1982.

4.1. AIR AND BIOMASS TEMPERATURE CHANGE

Thom (1975) suggested that for calculation of storage in the biomass ( $Q_v$ ), a representative  $\delta T$  may adequately approximate  $\delta T_b$ . On the basis of the data for this forest, this is not the case. The different behaviour of  $\delta T$  and  $\delta T_b$  is illustrated for two days (Figure 2). July 22 was a dry day and June 19 a very wet day. When the canopy is wet, the hourly change of air temperature is small and essentially the same at all three levels, and, as expected, when a rain event occurs, the value of  $\delta T$  decreases, e.g., at 0900, from 1200 to 1400, and at 2100. The  $\delta T_b$  values do not appear to respond directly to the

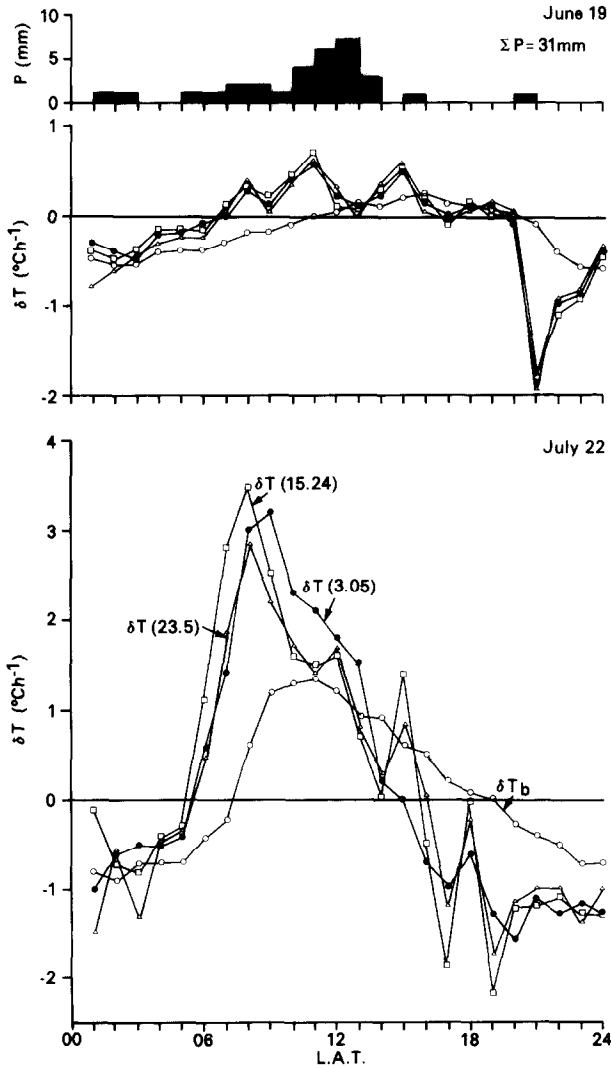


Fig. 2. Diurnal pattern of air and biomass temperature change ( $\delta T$  and  $\delta T_b$ ) for June 19 and July 22, 1982. July 22 was a dry day, whereas June 19 was wet (31 mm). Air temperature was measured at 3.05, 15.24, and 23.5 m. The curves are not identified for June 19 in order to avoid clutter.

occurrence of precipitation, but rather show a slow, gradual increase from negative values in the morning to small positive values in the afternoon and back to negative values from 2100 onward. In contrast, for July 22, the  $\delta T$  curves reach a maximum positive value early in the morning. The curves for the middle and upper levels are highly correlated and peak at 0800, whereas the curve for the lowest level lags the other two by approximately one hour, reaching a peak at 0900. For the remainder of the daylight period, all  $\delta T$  curves trend downward, becoming negative at 1600. The obvious minimum at 1700 is a result of a very low value of net radiation ( $59 \text{ W m}^{-2}$ ) as a result of cloud build-up, followed by a recovery to  $118 \text{ W m}^{-2}$  at 1800 when the cloud dissipated. At this time,  $\delta T$  at the lowest level shows a smaller response than those at the higher levels because of the insulating effect of the canopy. The  $\delta T_b$  curve shows the same basic response as that for  $\delta T$  for the whole day except that it lags the  $\delta T$  curves by approximately three hours, and the absolute values of  $\delta T_b$  are smaller.  $\delta T_b$  peaks in the late morning at 1100, becoming negative by 2000. There is no evidence of short-term changes in  $\delta T_b$  as compared to  $\delta T$ . Clearly, if air temperature change at one level were chosen to represent the biomass temperature change, the agreement would be poor from sunrise to midday and from sunset until midnight. In the early morning, all curves are very similar, and they also agree quite well in the early afternoon, especially when the canopy is dry. However,  $\delta T$  should not be substituted for  $\delta T_b$  as a general rule.

#### 4.2. HOURLY STORAGE TERMS

The diurnal behaviour of the storage terms is illustrated for July 22 (Table II). For the day as a whole, the overall storage ( $Q_s$ ) is of greatest significance, as a fraction of  $Q^*$ , at night and during the transition periods around sunrise and sunset. At night, with energy being released from all the stores,  $Q_s$  typically lies between  $-20$  and  $-40 \text{ W m}^{-2}$ . Normally,  $Q_v$  is the largest individual flux. In the early morning (0100 to 0500),  $Q_g$  and  $Q_a$  are of a similar size, smaller than  $Q_v$ , and are relatively constant over time. However,  $Q_w$  is quite variable but very small. Late in the day, 2000 to 2400,  $Q_g$  is insignificant, and the other three storage fluxes are of similar magnitude. All are fairly constant in time except for  $Q_w$  at 2200 when a larger (more negative) value occurs. At night,  $Q_s$  is typically between 40 and 50% of  $Q^*$ , but values higher than this can occur. At sunrise and sunset, the ratio of  $Q_s$  to  $Q^*$  exceeds 1.0 but only because the values of both fluxes tend toward zero. In the daytime period, the storage is dominated by  $Q_v$  and  $Q_g$ . However, from sunrise until midday,  $Q_a$  is significant, as is implied in the  $\delta T$  distribution (Figure 2). As a term in the overall energy budget during the daytime,  $Q_s$  is most important in the forenoon and late afternoon when it is equal to or greater than 10% of  $Q^*$ . In the early afternoon, it is less than 10% of  $Q^*$ . From the point of view of accurate assessment of hourly convective fluxes for forests, using the energy balance method, it is necessary to evaluate the storage terms. In many energy balance studies, only  $Q_g$  is measured, but the results from this forest clearly show that  $Q_v$  should also be evaluated as a bare minimum. As far as sensible and latent heat storage in the air are concerned, the former is more important, especially in the forenoon.

TABLE II

Hourly values of net radiation ( $Q^*$ ) and storage terms for July 22, 1982. Units are  $W m^{-2}$ . No precipitation fell on this day, and the canopy was dry.

Time	$Q^*$	$Q_g$	$Q_a$	$Q_w$	$Q_v$	$Q_s$	$Q_g/Q^*$	$Q_a/Q^*$	$Q_w/Q^*$	$Q_v/Q^*$	$Q_s/Q^*$
1	-53.7	-5.1	-6.2	-11.3	-14.8	-37.3	0.095	0.115	0.210	0.275	0.695
2	-55.0	-4.3	-4.5	-1.0	-16.6	-26.4	0.078	0.082	0.018	0.302	0.480
3	-41.9	-4.9	-6.2	1.2	-12.9	-22.7	0.117	0.147	-0.029	0.308	0.543
4	-23.6	-4.9	-3.1	-4.6	-12.9	-25.5	0.208	0.131	0.197	0.548	1.083
5	-14.4	-4.9	-2.4	-4.5	-12.9	-24.6	0.340	0.165	0.310	0.897	1.712
6	35.3	-1.3	5.2	0.2	-7.4	-3.2	-0.035	0.148	0.006	-0.209	-0.091
7	195.0	3.6	14.5	7.5	-3.7	21.9	0.019	0.074	0.038	-0.019	0.112
8	369.1	9.2	22.3	6.5	11.1	49.0	0.025	0.060	0.018	0.030	0.133
9	501.3	12.5	18.7	-0.1	22.1	53.2	0.025	0.037	-0.000	0.044	0.106
10	526.2	13.7	13.0	4.0	24.0	54.7	0.026	0.025	0.008	0.046	0.104
11	629.6	16.4	11.9	15.5	25.8	69.6	0.026	0.019	0.025	0.041	0.111
12	662.3	15.6	11.9	-10.1	22.1	39.5	0.024	0.018	-0.015	0.033	0.060
13	633.5	12.0	7.1	-14.3	16.6	21.4	0.019	0.011	-0.023	0.026	0.034
14	445.0	14.0	0.9	4.1	16.6	35.7	0.032	0.002	0.009	0.037	0.080
15	445.0	9.1	5.2	7.4	11.1	32.8	0.020	0.012	0.017	0.025	0.074
16	267.0	7.7	-2.8	29.2	9.2	43.2	0.029	-0.011	0.109	0.035	0.162
17	58.9	3.4	-9.7	21.4	3.7	18.8	0.058	-0.165	0.363	0.063	0.319
18	117.8	4.2	-1.9	2.8	1.8	6.9	0.036	-0.016	0.023	0.016	0.059
19	-6.5	2.8	-12.6	-0.3	0.0	-10.0	-0.427	1.920	0.041	0.000	1.535
20	-28.8	-1.3	-9.5	-4.6	-5.5	-20.9	0.046	0.329	0.159	0.192	0.726
21	-57.6	-0.5	-7.8	-9.9	-7.4	-25.7	0.009	0.136	0.173	0.128	0.446
22	-66.8	-0.5	-8.1	-24.2	-9.2	-42.0	0.008	0.121	0.363	0.138	0.629
23	-64.1	-2.6	-9.0	-6.1	-12.9	-30.6	0.040	0.140	0.095	0.201	0.477
24	-66.8	-1.8	-8.5	-8.4	-12.9	-31.6	0.026	0.128	0.125	0.193	0.473

#### 4.3. DAILY AND DAYTIME STORAGE

Whenever the data are aggregated into daily and daytime totals, the importance of the storage terms changes compared to the hourly values. For this study, daytime is defined as the period of the day when  $Q^*$  is positive. For daily periods over the whole 38-day sample, the importance of storage is, on average, low; the mean value of  $Q_s/Q^*$  is only 1.4% (Table III). However, this does not mean that storage can be ignored on a daily basis because, for overcast days when the daily total of net radiation is small ( $< 10 MJ m^{-2}$ ), and on days with prolonged precipitation or when the canopy is drying following precipitation, the comparative size of  $Q_s$  is much larger: 5–10% of  $Q^*$ . Furthermore,  $Q_s$  can be negative or positive. This is illustrated for five selected days: June 19, 25, 29, July 28, and August 10. On June 19, there was prolonged, heavy precipitation (Figure 1), and  $Q_g$  is the only positive storage flux on a daily basis. All other storage fluxes are negative with  $Q_v$  being the largest. The release of heat from the trees dominates the daily value of  $Q_v$ . It was only in the afternoon that the trees gained energy, but then by only a small amount. The daily negative values of  $Q_a$  and  $Q_w$  combined are approximately equal to the positive value of  $Q_g$ , and the overall negative  $Q_v$  dominates  $Q_s$ . A similar pattern exists for June 29 and July 28. The values of  $Q_a$  and  $Q_w$  on June 29



TABLE III  
Summary of daily totals of storage terms, Petawawa, 1982

	$Q^*$ (MJ)	$Q_g$ (kJ)	$Q_a$ (kJ)	$Q_w$ (kJ)	$Q_c$ (kJ)	$Q_s$ (kJ)	$Q_g/Q^*$	$Q_a/Q^*$	$Q_w/Q^*$	$Q_v/Q^*$	$Q_s/Q^*$
June 16	10.6	257.4	-94.7	-169.7	-99.6	-106.6	0.024	-0.009	-0.016	-0.009	-0.010
June 17	16.5	428.4	79.4	57.6	192.5	757.9	0.026	0.005	0.003	0.012	0.046
June 18	15.5	369.5	13.7	76.5	6.6	466.2	0.024	0.001	0.005	0.000	0.030
June 19	2.4	175.9	-89.6	-103.9	-265.5	-285.1	0.072	-0.037	-0.043	-0.110	-0.119
June 20	15.9	307.0	26.5	19.6	106.2	459.2	0.019	0.002	0.001	0.007	0.029
June 21	13.8	399.4	39.3	26.5	0.0	465.2	0.029	0.003	0.002	0.000	0.034
June 22	16.2	332.2	-41.0	-1.0	13.3	303.5	0.021	-0.003	-0.000	0.001	0.019
June 23	16.5	298.1	-16.2	-61.0	26.6	247.5	0.018	-0.001	-0.004	0.002	0.015
June 24	14.8	404.7	50.4	107.3	99.6	661.9	0.027	0.003	0.007	0.007	0.045
June 25	4.8	455.1	49.5	-14.0	-13.3	477.3	0.095	0.010	-0.003	-0.003	0.100
June 26	21.0	72.9	-114.4	-91.5	-33.2	-166.2	0.003	-0.005	-0.004	-0.002	-0.008
June 27	19.6	536.0	105.0	105.9	172.6	919.5	0.027	0.005	0.005	0.009	0.047
June 28	18.0	597.6	78.5	148.1	119.5	943.8	0.033	0.004	0.008	0.007	0.053
June 29	3.7	353.4	-127.2	-206.9	-272.2	-252.8	0.095	-0.034	-0.055	-0.073	-0.068
June 30	12.1	64.4	-79.4	-121.1	-146.0	-282.1	0.005	-0.007	-0.010	-0.012	-0.023
July 16	13.3	684.4	59.7	58.9	59.7	862.8	0.052	0.005	0.004	0.005	0.065
July 17	15.9	658.7	-33.3	-22.1	33.2	636.5	0.042	-0.002	-0.001	0.002	0.040
July 18	17.1	523.6	8.5	-79.1	-13.3	439.8	0.031	0.000	-0.005	-0.001	0.026
July 19	18.2	116.3	-205.7	-285.9	-278.8	-654.1	0.006	-0.011	-0.016	-0.015	-0.036
July 20	17.3	66.8	-24.8	-72.0	-106.2	-136.2	0.004	-0.001	-0.004	-0.006	-0.008
July 21	19.0	252.0	89.6	165.7	152.7	660.0	0.013	0.005	0.009	0.008	0.035
July 22	15.9	332.4	66.6	1.1	126.1	526.2	0.021	0.004	0.000	0.008	0.033
July 23	18.3	20.3	-105.8	-136.5	-185.9	-407.8	0.001	-0.006	-0.007	-0.010	-0.022
July 24	18.1	273.3	153.6	34.8	185.9	647.6	0.015	0.008	0.002	0.010	0.036
July 25	8.2	390.6	-30.7	294.2	26.6	680.6	0.048	-0.004	0.036	0.003	0.083
July 26	18.2	-71.6	-121.2	-280.8	-219.1	-692.7	-0.004	-0.007	-0.015	-0.012	-0.038
July 27	15.9	165.8	78.5	103.4	73.0	420.8	0.010	0.005	0.007	0.005	0.027
July 28	3.8	122.5	-67.4	-0.4	-285.5	-230.7	0.032	-0.018	-0.000	-0.075	-0.061
July 29	15.4	161.2	-58.9	-98.3	53.1	57.1	0.010	-0.004	-0.006	0.003	0.004
July 30	12.9	378.9	118.6	142.4	172.6	812.6	0.029	0.009	0.011	0.013	0.063
Aug. 07	12.4	422.1	43.5	239.2	53.1	757.9	0.034	0.004	0.019	0.004	0.061
Aug. 08	7.2	352.5	32.4	37.2	46.5	468.6	0.049	0.005	0.005	0.006	0.065
Aug. 09	13.9	209.9	-133.1	-340.7	-53.1	-317.1	0.015	-0.010	-0.025	-0.004	-0.023
Aug. 10	8.3	-210.9	-58.0	30.7	-318.6	-556.9	-0.025	-0.007	0.004	-0.038	-0.067
Aug. 11	8.8	-125.0	-16.2	-41.8	-46.5	-229.5	-0.014	-0.002	-0.005	-0.005	-0.026
Aug. 12	8.0	-23.3	35.0	46.9	33.2	91.9	-0.003	0.004	0.006	0.004	0.011
Aug. 13	9.4	102.0	36.7	65.4	92.9	297.1	0.011	0.004	0.007	0.010	0.032
Aug. 14	14.4	202.8	1.7	-13.6	139.4	330.3	0.014	0.000	-0.001	0.010	0.023

appear too high in comparison to the other selected days. However, on this day heavy cloud persisted up to late afternoon (1600) when the sky cleared. As a result, after sunset, air temperature and vapour pressure decreased steadily under the influence of strong longwave radiation loss. It was this latter part of the day which caused the large negative values of  $Q_a$  and  $Q_w$ . On August 10, the pattern of  $\delta T_b$  was very similar to that of June 19. However, the negative value of  $Q_v$  is associated with a negative daily total

of  $Q_g$  which combine to produce an overall negative value of  $Q_s$  which is approximately 6% of net radiation. In contrast, June 25, an overcast day with only 1 mm of rain, had trivial amounts of storage in the canopy air and the biomass, and the daily storage is dominated by the soil heat flux.  $Q_s$  accounted for 10% of  $Q^*$ , and  $Q_g$  is 9.5% of  $Q^*$ .

For daytime periods, the total storage is an important term in the energy balance of the forest (Figure 1), and is positive for the whole sample period. Two distinct regimes

TABLE IV  
Summary of daytime totals of storage terms, Petawawa, 1982

	$Q^*$ (MJ)	$Q_g$ (kJ)	$Q_a$ (kJ)	$Q_w$ (kJ)	$Q_v$ (kJ)	$Q_s$ (kJ)	$Q_g/Q^*$	$Q_a/Q^*$	$Q_w/Q^*$	$Q_v/Q^*$	$Q_s/Q^*$
June 16	11.6	431.7	59.7	-110.7	166.0	546.7	0.037	0.005	-0.010	0.014	0.047
June 17	17.6	623.6	313.2	100.0	577.5	1614.4	0.035	0.018	0.006	0.033	0.092
June 18	16.2	417.4	149.4	17.7	285.5	869.9	0.026	0.009	0.001	0.018	0.054
June 19	2.5	267.5	62.3	87.0	-39.8	377.0	0.105	0.025	0.034	-0.016	0.148
June 20	16.8	452.3	149.4	77.2	391.7	1070.6	0.027	0.009	0.005	0.023	0.064
June 21	14.4	484.6	175.0	99.0	258.9	1017.5	0.034	0.012	0.007	0.018	0.071
June 22	17.1	488.3	57.2	66.6	312.0	924.1	0.029	0.003	0.004	0.018	0.054
June 23	17.7	525.8	163.0	-14.2	365.1	1039.7	0.030	0.009	-0.001	0.021	0.059
June 24	15.8	613.6	256.1	29.6	418.2	1317.5	0.039	0.016	0.002	0.027	0.084
June 25	5.1	444.1	125.5	152.8	59.7	78.2	0.088	0.025	0.030	0.012	0.155
June 26	22.7	445.1	314.1	6.5	438.1	1203.8	0.020	0.014	0.000	0.019	0.053
June 27	20.6	760.1	379.8	154.5	597.5	1891.9	0.037	0.018	0.008	0.029	0.092
June 28	19.0	671.4	303.0	157.0	511.2	1642.6	0.035	0.016	0.008	0.027	0.087
June 29	4.5	391.7	63.2	71.2	-39.8	486.2	0.087	0.014	0.016	-0.009	0.107
June 30	14.1	420.3	186.9	63.0	305.4	975.6	0.030	0.013	0.004	0.022	0.069
July 16	14.1	670.7	207.4	334.7	345.2	1558.0	0.047	0.015	0.024	0.024	0.110
July 17	16.9	671.1	87.1	-163.1	338.6	933.6	0.040	0.005	-0.010	0.020	0.055
July 18	18.0	517.4	140.8	23.0	345.2	1026.4	0.029	0.008	0.001	0.019	0.057
July 19	20.2	359.6	120.3	-167.5	205.8	518.2	0.018	0.006	-0.008	0.010	0.026
July 20	19.6	386.9	291.9	40.9	491.2	1210.9	0.020	0.015	0.002	0.025	0.062
July 21	20.7	472.3	448.1	121.4	677.1	1718.9	0.023	0.022	0.006	0.033	0.083
July 22	17.6	433.0	346.5	266.1	551.0	1596.6	0.025	0.020	0.015	0.031	0.091
July 23	20.9	299.6	280.8	-105.6	398.3	873.1	0.014	0.013	-0.005	0.019	0.042
July 24	19.8	431.6	445.5	35.2	610.7	1541.1	0.022	0.022	0.003	0.031	0.078
July 25	9.1	347.8	167.3	211.7	239.0	965.9	0.038	0.018	0.023	0.026	0.106
July 26	19.9	277.6	192.0	-178.4	278.8	570.1	0.014	0.010	-0.009	0.014	0.029
July 27	17.3	331.9	280.8	78.2	484.6	1175.5	0.019	0.016	0.005	0.028	0.068
July 28	4.4	143.4	-8.5	24.0	-112.9	46.0	0.032	-0.002	0.005	-0.025	0.010
July 29	17.1	444.3	242.4	-83.1	365.1	968.7	0.026	0.014	-0.005	0.021	0.057
July 30	13.8	350.7	329.5	144.8	524.4	1349.3	0.025	0.024	0.011	0.038	0.098
Aug. 07	13.2	462.7	122.9	289.7	331.9	1207.2	0.035	0.009	0.022	0.025	0.092
Aug. 08	7.4	392.1	165.6	165.6	252.3	975.6	0.053	0.022	0.022	0.034	0.131
Aug. 09	15.4	351.3	139.1	-32.6	292.1	452.9	0.023	0.009	-0.021	0.019	0.029
Aug. 10	9.3	32.2	23.9	103.6	59.7	219.5	0.003	0.003	0.011	0.006	0.024
Aug. 11	9.4	141.0	140.8	-13.4	172.6	441.0	0.015	0.015	-0.001	0.018	0.047
Aug. 12	8.7	185.1	107.5	36.4	252.3	581.4	0.021	0.012	0.004	0.029	0.067
Aug. 13	10.2	236.9	184.4	66.8	318.6	806.7	0.023	0.018	0.007	0.031	0.079
Aug. 14	15.9	403.6	259.5	-20.2	471.3	1114.2	0.025	0.016	-0.001	0.030	0.070

are evident. In the early part of the sample period, June 16 to 30, daytime storage varies from a minimum of 5% to a maximum of 15% of  $Q^*$ . The maximum occurs on two days, June 19 and 25, when  $Q^*$  was very small (Table IV). For the remainder of the sample period in late July and early August, the total storage is lower on average even though on many days the value of  $Q_s/Q^*$  is as high as for the earlier period. The relative importance of each storage term is illustrated in Figure 3. In June, the soil storage flux dominates the overall storage as a result of the very high soil moisture values at this time. The biomass storage term is next in overall importance, except for the special conditions which prevailed on June 19, 25, and 29, resulting in small and sometimes negative biomass storage. In July and August, the soil heat storage is a less important term;  $Q_g$  and  $Q_v$  are approximately the same magnitude and larger than  $Q_a$  and  $Q_w$ .  $Q_a$  is never more than 2% of  $Q^*$  and is positive for all days except for July 28 when it is insignificant but negative. The  $Q_w$  storage term fluctuates between positive and negative values which seldom are more than 1% of  $Q^*$ .

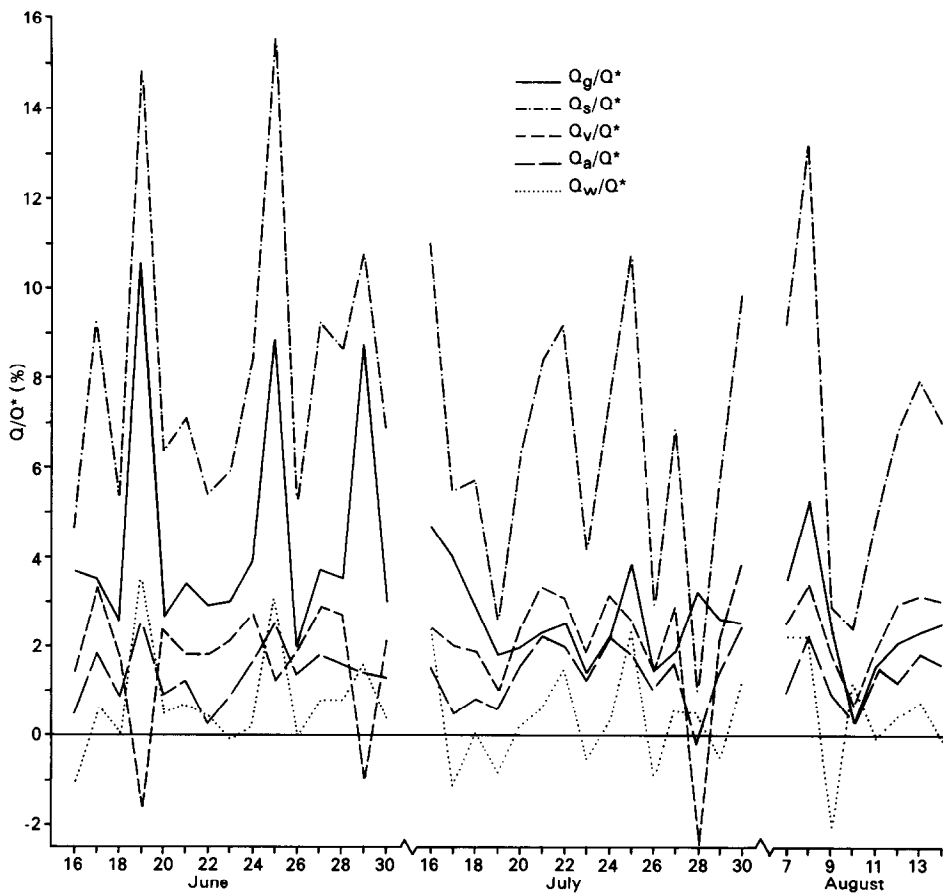


Fig. 3. Daytime totals of the energy balance storage terms as a fraction of net radiation.

## 5. Conclusions

The storage terms are important components in the energy balance of the forest canopy at Petawawa. The soil and biomass storage terms are usually the largest. The former is the larger when the soil moisture is high ( $> 20\%$  by volume); when the soil moisture is  $< 20\%$ , the two are of similar size. For the hourly estimation of this forest's energy balance it is recommended, on the basis of these results, that all of the storage terms be evaluated. It is especially critical that estimates be made early in the morning when the air and biomass temperature are increasing most rapidly. Also, close to sunrise and sunset and during the night, the total storage is large ( $\geq 50\%$  of  $Q^*$ ), relative to the other terms of the energy balance, even though its absolute size is usually small. Careful measurement of total storage at such times could be crucial in finding accurate convective fluxes of the proper sign.

The biomass storage should be calculated from measurements of biomass temperature change; a 'representative' air temperature change should not be used because its diurnal evolution is different from that of the biomass. For days when the canopy is dry, the rate of change in air temperature peaks early, between 0800 and 0900, and the rate of change in biomass temperature lags by up to three hours. Very early in the day, before sunrise, and in the early afternoon, the hourly rates of change of air and biomass temperature are comparable in size, but for the rest of the day, the former is much larger. When the canopy is wet, there are still differences between air and biomass temperature, the former being more variable and much more responsive to rainfall. When precipitation occurs, the rate of change in air temperature decreases, whereas the rate of change in biomass temperature shows little short-term fluctuation.

Even though the importance of the overall storage,  $Q_s$ , decreases when daily totals of energy flows are considered, it is still possible for it to equal 5–10% of  $Q^*$  under particular circumstances. For instance, when  $Q^*$  is low ( $< 10 \text{ MJ day}^{-1}$ ), during overcast days or during rainfall, the relative importance of  $Q_s$  is significant. When the canopy is wet and  $Q^*$  is low, there is typically a release of energy from the biomass and  $Q_s$  is negative for the whole day. However, when the canopy is dry and the net radiation is high, the daily storage seldom exceeds 2–3% of  $Q^*$ , and it can safely be ignored. Often, the small value of daily total energy storage under dry conditions results from a cancellation of one storage term by another.

On the basis of daytime totals of storage and net radiation, it was found that  $Q_s/Q^*$  was always positive. Two distinct regimes were evident for this forest. First, early in the analysis period from June 16 to 30, the soil heat storage was the largest of the storage terms as a result of high soil moisture conditions. The biomass storage was next in order of importance. In July when the soil moisture was lower, the biomass and soil storage terms were of similar size. For all days, the sensible and latent heat storages of the air in the canopy were small.  $Q_a$  seldom exceeded 2% of  $Q^*$  and  $Q_w$  was typically slightly smaller, especially when the canopy was dry and the soil moisture low.

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