6.7 CAN THE ENERGY BALANCE RESIDUAL BE USED TO ESTIMATE BOREAL FOREST EVAPOTRANSPIRATION SUCCESSFULLY?

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1. INTRODUCTION

Forest evapotranspiration (ET) is being widely measured at sites globally, often linked to the international FLUXNET networks where the main objective is the estimate of the carbon dioxide (CO_2) exchange between forests and the atmosphere (e.g., Law et al. 2002). However, there are many more sites where ET measurements are needed to answer questions related to water balance or forest physiology. The eddy covariance technique has become the standard measurement technique because of its relative simplicity, and the availability of fast-response instruments that can measure both water vapor and CO_2. However if CO_2 fluxes are not desired, the cost and complexity of a fast-response water vapor sensor can be a barrier for ET measurement. An alternative is the Bowen ratio method where the gradients of temperature and water vapor are measured along with net radiation (R_n) and ground heat flux density (G) to resolve the latent heat flux density (λE) (e.g., Price and Black 1991). However, this method has largely been replaced by direct eddy covariance measurements, partly to overcome issues with dissimilar footprints when a gradient is measured.

We recognize that it is desirable to measure ET using eddy covariance directly. But is it reliable to measure the other energy balance components and solve for ET by the residual? Such a scheme has been used in various applications in the past where λE was solved as the residual of R_n, G and the sensible heat flux density (H) (Amiro and Wuschke 1987; Adams et al. 1991; Blanford and Gay 1992). However, we need to be better evaluate this against measured ET with the express purpose of using the residual in an operational method. This energy balance residual method would still normally require R_n and H to be measured on a tower above a forest, with H measured using eddy covariance. Most flux towers measure R_n, H and G anyway to check energy balance closure and to correct for density effects on the CO_2 flux, when needed.

One of the main concerns has been that the energy balance does not close perfectly, with apparent missing energy when we compare the turbulent terms ($H + \lambda E$) with the available energy ($R_n - G$). This lack of closure has been observed consistently over the past two decades since fast-response water vapor sensors became widely available for researchers to measure each term. In a survey of about 50 site years of FLUXNET data, Wilson et al. (2002) documented the general lack of closure with about 20% of the energy missing. Closure tends to be worse at night during periods of low turbulence and the carbon dioxide flux community has recognized the issue, often excluding data below a friction velocity (u_*) threshold (e.g., Goulden et al. 1996). This has led to the development of gap filling techniques for both CO_2 fluxes and for energy fluxes (e.g., Falge et al. 2001). Twine et al. (2000) give a good overview of the issues dealing with closure. They conclude that turbulent flux measurements should be adjusted to close the energy balance, ideally while preserving the Bowen ratio ($H/\lambda E$).

The present goal is to evaluate whether the energy balance residual can be used to reliably estimate ET over forests, so that this method can be applied in water balance studies. We test this using data sets from three different-aged boreal forest sites in central Saskatchewan, Canada. These sites are part of the Boreal Ecosystem Research and Monitoring Sites (BERMS), where flux towers have been operating for over a decade following the BOREAS experiment (Sellers et al. 1997).

2. METHODS

2.1 Flux Measurements

The field data were collected in central Saskatchewan, in the southern part of the boreal forest (approximately 54°N, 106°W). We used three post-fire sites that had been burned in 1977 (F77), 1989 (F89) and 1998 (F98). All of these sites had been dominated by jack pine (*Pinus banksiana*) with some black spruce (*Picea mariana*) prior to the fires. At the time of measurement, F77 was dominated by a jack pine canopy about 7 m tall, F89 had a mixed canopy of jack pine and trembling aspen (*Populus tremuloides*) about 4 m tall, and F98 was jack pine and trembling aspen about 1-2 m tall with dead trees

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to a height of about 20 m. The leaf area index was about 3.4, 3, and 1 at the F77, F89 and F98 sites, respectively. At each site, measurements were made above the canopy on either scaffold (F98) or triangular (F77, F89) towers.

Net radiation was measured at the top of the tower at each site using a four-component net radiometer (Kipp and Zonen Model CNR1, Delft, The Netherlands). At each site, three ground heat flux plates (Thornthwaite Model 610, Pittsgrove, NJ, U.S.A.) were placed at a depth of 2 cm below the surface, with the top of the surface defined where the forest organic layer starts, below the litter and actively growing moss. At the F98 and F89 sites, this was in mineral soil because of a very shallow or missing organic layer. Three 24-gauge thermocouples were also placed at this depth to measure energy storage between the flux plates and the surface. Three soil moisture probes (Campbell Scientific Canada model CS616, Edmonton, AB, Canada) were placed vertically into the soil to give mean soil moisture to a depth of about 30 cm. We calculated soil energy storage in the top 2 cm using the temperature change over a 30-min period and a volume fraction of 0.55 for mineral soil (heat capacity = 2×10^6 J m^{-3} K^{-1}) with the moisture fraction from the probes.

H and λE were measured using eddy covariance. Fast-response wind velocities and temperature were measured using a three-dimensional sonic anemometer/thermometer (Campbell Scientific Canada model CSAT3, Edmonton, AB, Canada). Fast-response water vapor measurements were made with an open-path infrared gas analyzer (LiCor model LI7500, Lincoln, NE, U.S.A.). The anemometer and water vapor signals were measured using a datalogger (Campbell Scientific Canada model 23X, Edmonton, AB, Canada) at a rate of 10 samples s^{-1}, whereas the net radiometer and soil measurements were at a rate of 1 sample s^{-1}. The turbulent flux cross-products and covariances were calculated on-line. A coordinate rotation was performed so that the mean vertical velocity was set to zero (Tanner and Thurtell 1969). All measurements are 30-min means. Additional information on the sites and measurements is given in Amiro et al. (2006a,b).

2.2 Determination of Measured ET

The open-path infrared gas analyzer is susceptible to periods of rain and we excluded turbulent flux data when the sonic anemometer had more than a 5% loss in a 30-min period. In addition, we filtered flux data using lower and upper limits of -150 and 500 W m^{-2} for H and -15 and 500 W m^{-2} for λE. We then filtered the day-time data using a cutoff value for u_* of 0.25 m s^{-1} for all sites. This value was based on averaging net ecosystem exchange (NEE) data according to u_* in 10 bins with an equal number of points, and then selecting the threshold at 0.8 of the average NEE of the last three bins. This is our standard quality-control procedure for turbulent fluxes of NEE, which we also apply to H and λE.

Gaps of two hours or less (i.e., four data points) were filled through linear interpolation. Longer gaps were filled through a regression of λE on R_n–G using a moving-window filter of 240 points that was moved in an increment of 48 points (Amiro et al. 2006a). Night-time gaps in λE were set to zero.

Potential imbalance of energy closure was simplified to a regression between the turbulent terms (H and λE) and the available energy (R_n-G):

$$H + \lambda E = f\,(R_n - G) \qquad (1)$$

where f is the regression coefficient, which usually has a value of less than one, assuming a zero intercept (e.g., Wilson et al. 2002). Assuming that there is an equal fractional loss of energy in each of H and λE, the measured latent heat flux density, λE_m, needs to be adjusted by 1/f to represent the best estimate of the water flux using the energy balance check. In the present study, we have set f = 1 (i.e., assuming perfect energy balance closure) to calculate the measured evapotranspiration, ET_m, from λE_m .

2.3 Calculation of ET using the Energy Balance Residual

The calculated evapotranspiration, ET_c, was based on the calculated latent heat flux, λE_c, as:

$$\lambda E_c / f = R_n - G - H/f. \qquad (2)$$

Note that this assumes energy balance closure adjustment through the parameter f and follows from Equation (2). Again, we set f = 1 in the present study for reasons presented in the results section. As described in the previous section, H was filtered for a u_* threshold and for upper and lower limits. Gaps in H were then filled identically to those for λE using a regression on R_n-G. For the data sets used in this paper, we did not have gaps in R_n-G that were longer than two hours, so there was no additional gapfilling of this quantity.

It is likely that missing additional storage terms in Equation (2) will cause periods when λE_c is clearly incorrect. This is especially noticeable at night when λE should be close to zero because of stomatal closure by plants, small vapor pressure gradients, and little energy to drive evapotranspiration. Recognizing energetic and physiological limitations, we set $\lambda E_c = 0$ when R_n-G ≤ 0. The implications are that both λE_c and λE_m are set to zero for most of the night period.

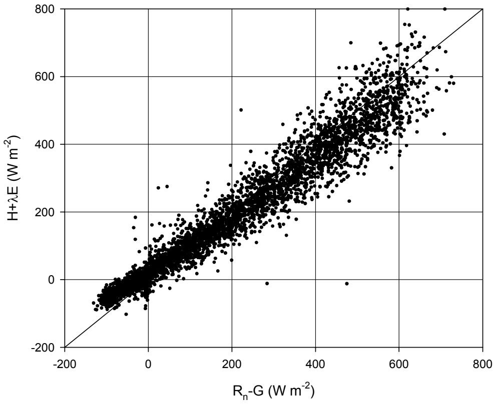
3. RESULTS AND DISCUSSION

3.1 Energy Balance Closure

The energy balance closure based on 30-min means from our sites varied slightly among years and sites, with r^2 values close to 0.9 (Table 1). The mean of all the data has a slope of 0.85. Closure on the order of 0.85 to 0.9 is common among many experiments (Wilson et al. 2002). The regressions shown in Table 1 also have an offset of about 23 W m^{-2}. This is non-trivial for a 30-min mean value and is quite consistent among the data sets. As an example, Fig. 1 shows that the offset really appears to be caused by a positive $H+\lambda E$ at low values of R_n-G. This is not unreasonable since there are many situations when R_n-G approaches zero but other storage terms or advection could provide the energy to drive $H+\lambda E$. In addition, the highest levels of R_n-G occur in the part of the day when the forest is gaining energy, so that we have not accounted for all energy storage, resulting in R_n-G being greater than $H+\lambda E$.

The regressions on the 30-min values clearly show that energy imbalance is an issue over short time scales. However, the means of R_n-G and $H+\lambda E$ over the full May 1 to September 30 period for quality-controlled and filtered data agree very well (Table 1) with a mean difference of only 0.4% for the 11 data sets. This indicates that longer-term averaging smoothes the storage quantities, resulting in close to perfect energy balance. This supports the selection of f = 1 in Equations 1 and 2.

Fig. 1. Energy balance for the 1977 site in 2006 for 30-min periods for May 1-September 30 following quality controls. The regression is $H+\lambda E = 0.86 (R_n\text{-}G) + 20$. The 1:1 line is shown for reference.



3.2 Estimates of Evapotranspiration (ET)

The dataset includes periods of both abnormally dry and wet years. We evaluate a dry year (2003) that was the last year of a three-year drought in the region, and a wet year (2005) which was the second year of a two-year consecutively wet period. The annual ET for these sites was calculated using thresholds and gap filling as indicated previously. It is clear that there is a range of annual ET that varies with site and year. In particular, the youngest site has lower ET than the older forests, and 2005 has greater ET than 2003 at all sites. This offers a wide range of data to test the technique with rainfall varying by a factor of two, and annual ET varying by about 70%.

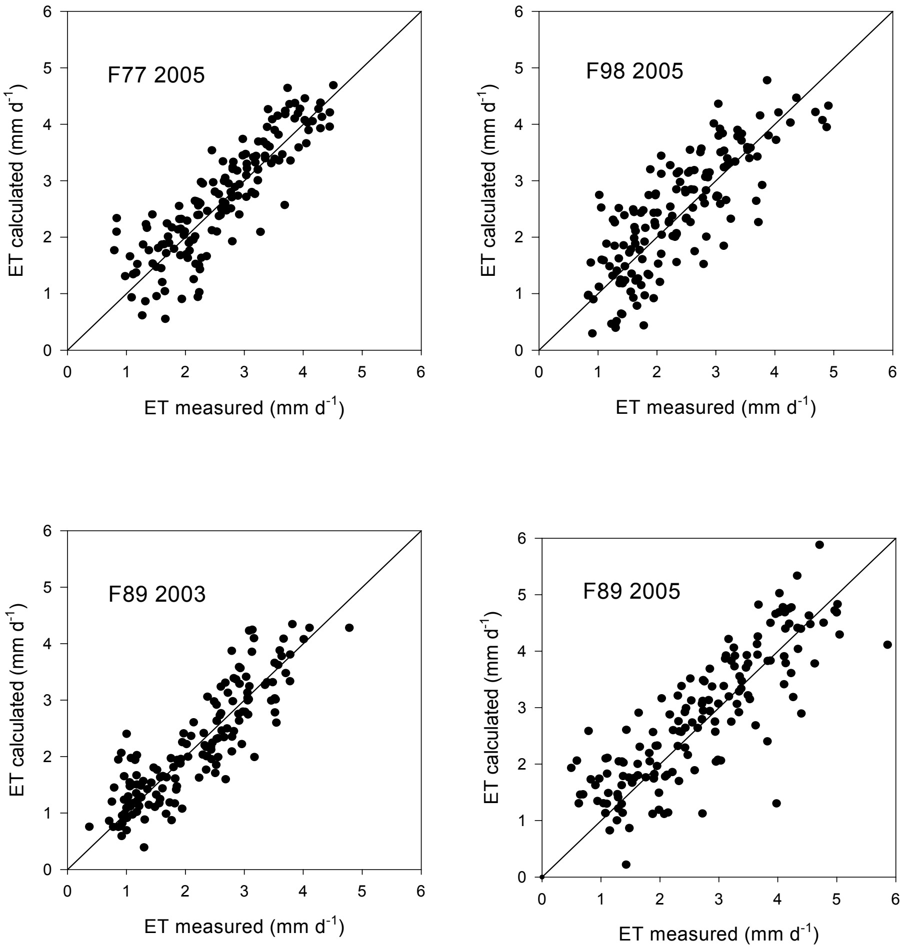
Gaps in the measured fluxes are mostly caused by precipitation events that affect both the sonic anemometer and the open-path infrared gas analyzer. There are some additional gaps created by the need to calibrate the infrared gas analyzer. In the current data set, measurement gaps during the growing season were 7, 10, 25, and 12% of the H data for the F98-2005, F89-2005, F89-2003, and F77-2005 data sets respectively. In comparison, 16, 16, 28 and 22% of the λE measurements were missing for these data sets, respectively, after quality control. The filtering for the u_* threshold created additional missing data of 17, 26, 24, and 23%. Hence, the λE measurements represent typically between 50 and 70% of the time period. The remainder of the period must be filled. For the energy balance residual method, R_n is essentially continuous (<0.01% missing), whereas the gaps in H are slightly less than those for λE.

Figure 2 shows relationships between calculated and measured daily ET for wet and dry years for the 1989 site and for the 1998 and 1977 sites during the wet year. The data cover the period from May 1 to September 30 in both years. There tends to be substantial day-to-day variability between ET_m and ET_c at the daily time scale, but the relationship is clear and does not depart substantially from the 1:1 line. Note that the daily totals assume perfect energy balance closure and have not been adjusted. Also note that the four panels show similar results even though there are three different sites.

Table 1: Energy balance closure for three boreal forest sites in Saskatchewan for 30-min periods. Units are in W m^{-2}. The data are for the May 1 to September 30 period each year, and only include values when $u_* > 0.25$ m s^{-1}.

Year burned	**Year measured**	**slope**	**offset**	**r^2**	**n**	**Mean R_n-G**	**Mean H+λE**
1998	2006	0.89	23	0.92	3985	157	163
	2005	0.81	35	0.90	4278	145	152
	2004	0.80	26	0.90	3666	148	145
	2003	0.84	22	0.89	4495	133	134
1989	2005	0.85	23	0.91	4760	172	169
	2004	0.85	23	0.93	5873	124	128
	2003	0.89	22	0.91	4148	173	175
1977	2006	0.86	20	0.94	5996	131	133
	2005	0.88	21	0.92	4593	172	172
	2004	0.87	18	0.94	4410	179	174
	2003	0.85	17	0.93	2506	145	141
Mean		**0.85**	**22.7**			**152.6**	**153.3**

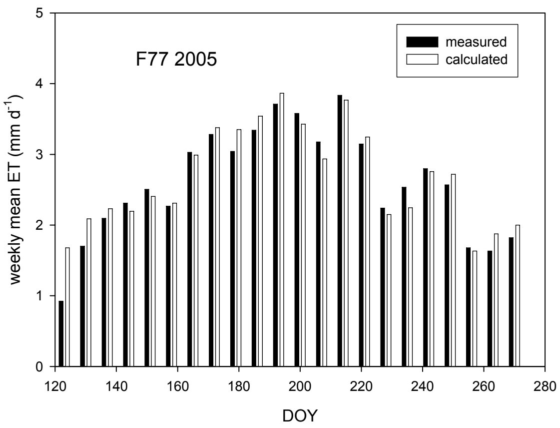
Fig. 2. Comparison of daily estimates of ET from the direct eddy covariance method (measured) and the energy balance residual method (calculated). Data for three sites are shown for a wet year(2005) and one site for a dry year (2003). The 1:1 line is shown for reference.



The differences between calculated and measured ET are even less when averaged over a weekly period (Fig. 3). Only a single site year is shown in Fig. 3, but the other sites have similar patterns. Weekly means show differences of typically about only 0.1 mm d^{-1} or about a few percent in mid-summer. The poorer agreement in the spring, before about day 130, is common and is likely caused by an underestimate of energy storage as the forest warms following winter. This overestimates ET_c because of the missing positive storage.

We also observe that the cumulative ET over the season has good agreement between the measured and calculated values for each of the four datasets (Fig. 4). The largest difference by the end of September was for the F89 site in 2005 which had an absolute difference of 22 mm on a total of 411 mm, or about a 5% overestimate. The consistent, but slight, overestimation of ET_c over ET_m is likely caused by no adjustment for energy balance closure. However, the differences, even cumulative over the growing season, were still less than 5%, so any adjustment would be minor. Adams et al. (1991) also found very good agreement between the energy balance residual method and the soil water balance in a forest clear cut over two years.

Fig. 3. Daily total ET averaged weekly for the F77 site in 2005.



3.3 Uncertainty Analyses

The uncertainty in the estimation of ET through energy balance residual has similar components to uncertainties in ET measurement using eddy covariance. It is likely that the uncertainty in measuring H is less than in the measurement of λE because of the relative simplicity of a temperature measurement compared to rapid fluctuations in water vapor. The accuracy of measuring the vertical wind velocity impacts both the measurement of λE and H. Additional uncertainties depend on whether λE_m is adjusted for energy balance closure. For example, perfect closure dictates that the adjusted measured λE, λE_a, is calculated as:

$$\lambda E_a = \lambda E_m (R_n\text{-}G) / (H + \lambda E_m) \quad (3).$$

For reference, let's look at a mid-summer day with Rn-G = 500 W m^{-2}, perfect energy balance closure, and the Bowen ratio (H/λE) being either 4 or 0.25. A 50 W m^{-2} (i.e., 10%) underestimation of Rn-G results in a 50 W m^{-2} reduction in λE_c, irrespective of the Bowen ratio. However, it results in 40 and 10 W m^{-2} reductions in λE_a at Bowen ratios of 0.25 and 4, respectively (10% in both cases). For comparison, a 10% underestimation of H changes λE_a by 8 W m^{-2} but changes λE_c by 10 and 40 W m^{-2} for Bowen ratios of 0.25 and 4, respectively. Hence it is clear that the energy balance residual method can have greater uncertainties if there are errors in R_n, G, or H measurements, but λE_a is still affected because of the closure issue. In addition, it is likely that λE_m is the most difficult measurement to make, ignoring storage terms over short periods of time. Hence, we are likely trading uncertainties without a clear advantage in using λE_m to estimate ET.

The choice of gap filling algorithms can have a large effect on the estimates (Falge et al. 2001). In recent years, the recognition that NEE at night is underestimated under low turbulent conditions has led to the questioning if all turbulent terms are underestimated (e.g., Twine et al 2000). Assuming that this is true, both H and λE are filtered, creating additional gaps. For NEE, these gaps are very important because of large night respiration. However, λE approaches zero at night, so errors in night gap filling have only a small effect on the daily estimate of ET. Our setting of $\lambda E_m = 0$ for night-time gaps, and $\lambda E_a = 0$ for cases when $R_n\text{-}G \leq 0$ gives similar night values and stresses the daytime measurements and calculations.

The issue of energy balance closure causes both an uncertainty and a bias, at least for short time scales. From the large number of observations at sites in the global Fluxnet network, it is clear that the turbulent fluxes usually under-estimate the available energy (e.g., Wilson et al. 2002). However, for our data sets, the longer-term mean shows excellent energy closure and we achieve less than a 5% difference for a cumulative annual estimate (Fig. 4). In addition, the convergence of gap-filling in λE_m and λE_c likely further minimizes some of the differences. We described this for night data previously, but daytime gap filling for λE_m relies on a regression with R_n-G, which would be correlated with λE_c. However, it could be fortuitous that the data sets used here have very good closure over the long-term. Recognizing that poorer closure is the norm at many sites, we need to consider that the energy balance residual technique may give higher ET estimates than direct measurements. This bias is likely an over-estimate of the order of about 5%, assuming that the turbulent fluxes are equally underestimated, and that the mean Bowen ratio is about one. It is important to note that the regression of our 30-min data did not show energy closure, whereas the longer-term mean balanced quite well.

Another issue is that λE_c has a mixed footprint, which must differ from that of λE_m. Although H will have a similar footprint to λE_m, R_n and G have smaller footprints. Hence, the estimate of λE_c has a local bias, so the location of the R_n and G measurements is very important. Clearly, there would be a benefit of more than one net radiometer in the footprint area as well as a high repetition in G measurements.

The accuracy of the residual energy balance method in the boreal forest does depend on how well energy storage can be estimated. This is because the period of maximum ET coincides with energy gain by the forest. For example, at our sites on a daily basis, G accumulates until early August, is approximately zero from early August until mid-September, and then becomes negative. Hence, the period of greatest ET in June and July has a sizable G that cannot be ignored. Further, the neglect of other storage terms, such as heating of the boles of trees (McCaughey and Saxton 1988), already causes an over-estimate of ET_c. As an example for the F77 site in 2005, the cumulative ET_c for the May 1 to September 30 period increases to 449 mm when using R_n only, compared to 411 mm for R_n-G. For comparison ET_m = 400 mm. For the younger F98 site in 2005, ET_c is 371 mm using R_n-G and 406 mm using R_n only, with ET_m = 359 mm. This is an overestimate of about 13% for these sites. Hence, we recommend that the storage terms should be measured as well as practical in forests during periods where storage is an important term. This is clearly true for forests with strong seasonal cycles such as the boreal forest.

In Figures 2 to 4, we have shown good agreement between calculated and measured ET for the main part of the growing season, selected as May 1 to September 30. However the agreement is not as good outside of this period. The snow-covered period usually shows a higher error in ET_c and this can be substantial during snowmelt. For example, at the F77 site in April 2005, ET_c was about 2 mm d^{-1} whereas ET_m was about 1 mm d^{-1}. This poorer agreement can be seen in the first two weeks of Figure 3. Good estimates of ET_c during this part of the year require much better accounting of all energy and the snowmelt period is especially difficult to evaluate (e.g., Pohl and Marsh 2006).

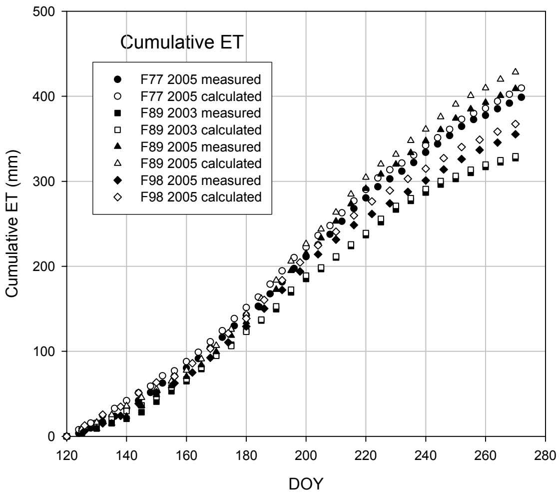
3.4 Recommendations for Use of the Energy Balance Residual Method

Our interest in using the energy balance residual method is linked to the need to measure ET at various forest sites at reduced cost and instrument maintenance. Hence, our goal is to omit the use of a fast-response water vapor sensor, which reduces cost, power consumption at remote sites, and calibration checks. However, this also puts increased importance on good measurements of R_n and H, as well as storage terms. These measurements are often easier to make than the direct measurement of λE and usually have fewer gaps.

It is clear that the agreement between ET_m and ET_c has quite a bit of scatter among 30-min means, and we do not recommend using the energy balance residual method for such short time scales. However, agreement is good on daily and weekly scales, with cumulative seasonal ET being very close. The need to fill gaps in ET_m results in as much as 50% of ET_m to be based on modeled relationships anyway.

The energy balance residual method does not work well during periods when storage terms are large compared to other fluxes, unless a large effort is placed on good measurements of storage. In particular in the boreal forest, early spring is not reliable during snow melt or when any of the storage terms are large and not measured well.

Fig. 4. Cumulative ET from May 1 to September 30 for four site years. Closed symbols are measured using eddy covariance and open symbols are calculated using the energy balance residual.



4. CONCLUSIONS

The energy balance residual method is a reasonable approach to estimate ET over forests. It agrees well with direct measurements of ET using eddy covariance even with the assumption of perfect energy balance closure. Part of this good agreement is because of the need to fell gaps in the measured ET, which are often based on energy balance relationships. However, experience at other sites with poorer energy closure indicate that the residual may over-estimate ET by about 5%, which adds some uncertain bias. The advantage of using the residual energy balance is the removal of the need to operate a fast-response water vapor sensor, which reduces the cost and calibration needs of a measurement system. The method is most accurate when the energy storage terms are well known, either through good quality measurements, or under conditions when storage is relatively small. Hydrological monitoring of evapotranspiration can be simplified using this technique.

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