

**Long-term water flux changes from converting old-growth pine forests to hardwood forests in northern Wisconsin**

**Final Report**

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Highlights and milestones of the Land Surface Hydrology Project were:

**1. A comprehensive database of vegetation, water fluxes, micrometeorology, remote sensing, soil moisture, tower flux, and process-based models were used in the first successful scaling-up exercise at the WLEF tower (Mackay *et al.*, 2002; Ahl *et al.*, 2003a,b,c).** Water fluxes at WLEF consist of two major sources coming from (1) tree transpiration, and (2) saturated soils in the forested wetlands. These two components of fluxes were shown to capture the total water flux from the footprint of the eddy covariance measurements at the WLEF tower. The results of this work show that water fluxes from forested wetlands, which are typically not considered in large scale remote sensing classification programs, need to be better represented. This study was chosen for the December 2002 cover of Global Change Biology. In addition to supporting water flux calculations around WLEF, the detailed forest cover classification was used to evaluate scaling effects on net primary productivity of using the MODIS fAPAR product.

**2. An essential bridge was developed between leaf and tower flux measurements with measurements of leaf water potential and transpiration among seven key species in the WLEF tower footprint (Ewers *et al.*, 2002; Ewers *et al.*, 2003).** Early succession species, aspen, transpired at two times the rate of the dominant northern hardwood, sugar maple, although leaf area index varied by only 15%. This is a significant result for modeling land surface processes with remote sensing, as it demonstrates that leaf area index alone cannot explain significant variability in water fluxes. Considerable inter-annual variability in water fluxes was found due to leaf area dynamics, insect defoliation, and changes in water table depth. However, despite all these effects minimum leaf water potential did not vary within a species among years.

**3. Accurate simulations of transpiration models and parameterization for the heterogeneous forests around WLEF (Mackay *et al.*, 2003a,b; Samanta and Mackay, 2003).** We developed a new parameterization scheme using fuzzy logic to select and restrict parameters in land surface models. We used this new logic to improve the accuracy of diurnal transpiration calculations. We used these results to calculate 30-minute resolution transpiration for the region at TM scale.

**4. We developed a parameterization scheme to use MODIS land surface temperature to estimate canopy stomatal conductance for simulation transpiration and photosynthesis (Mackay *et al.*, 2003c).** We have worked collaboratively with the MODIS MOD16 team to combine estimates for vapor pressure deficit from MODIS land surface temperatures to estimate species level canopy average stomatal conductance.

## Introduction

The last 100 years have seen drastic changes in the forest cover of northern Wisconsin. Aspen, northern hardwoods, and red pine have replaced large areas of clear-cut white pine and eastern hemlock. The only forested areas that have been untouched by direct management activities are forested wetlands. However, even these areas will be impacted by changes in water quality and flow management. Our research aims to investigate how changes in forest cover will impact regional water balance. Any resulting changes will feed back on the atmosphere and water table perhaps resulting in even greater changes in regional water budgets than land managers intend. This report details the results of two years of field data collection and the resulting modeling effort to explain the large differences we see in water use rates of the different forest cover types.

## Material and Methods

### Focused Field Measurements

We finished development of a site-specific land cover classification for the study site. Based on ATLAS imagery, which was flown at two heights, there is a 3m land cover product, which is used primarily for field guides, and a 15m land cover product (Figure 1). Both are field-verified using 324 permanent plots. Site-specific categories were selected to be disaggregated from IGBP land cover classes, in order to facilitate ties to global data products. We used the site-specific land cover classification map to identify the four dominant forest cover types selected for sap flux studies. The site-specific data is also the most significant variable for explaining the spatial variation of leaf area index within the region around the WLEF tower (Burrows *et al.*, 2002).

In order to adequately sample the forest cover types of northern Wisconsin, we chose four cover types representing more than 80% of the ground area within the foot print of an unusually tall (400 m) eddy covariance measurement. We measured sap flux in 8 trees of each species in the following cover types: conifer, aspen/fir, northern hardwoods, and forested wetlands. In each species of each cover type, we scaled point measurements of sap flux to whole tree water flux per unit xylem area ( $J_s$ ) using radial measurements through the conducting xylem and north and south circumferential measurements. In addition, we measured environmental conditions such as vapor pressure deficit ( $D$ ), soil moisture, and photosynthetically active radiation ( $Q$ ). We evaluated the response of water flux to environmental conditions at various time and spatial scales. We used time series and repeated measures analysis to investigate the impact of forest cover types and species on the diurnal and daily trends in water flux. The stand-level fluxes were scaled to the landscape through use of the site-specific forest cover classification. The scaled transpiration was compared against water fluxes measured at the WLEF tower. These measurements were made for a period of 57 days during the summer of 2000, and for the entire growing season of 2001.

### Regional Model

This focused set of field measurements is supported with the development of a new regional hydrologic model, which operates at 30 min intervals for canopy processes and daily intervals for soil water balance. The model can be operated in a stand-level mode for development of land cover prototypes, and in full landscape model with the option of integrating the land cover prototypes. Parameterization and sensitivity analysis of this new model was supported with the development of a new multi-objective Monte Carlo analysis method (Samanta and Mackay, 2003; Mackay *et al.*, 2003a,b,c). We have performed sensitivity analysis on a species-specific basis. The approach involves repeatedly randomly sampling parameter values from a hypercube, running the model, and then applying a series of objective functions that relate

simulated transpiration to sap flux observed transpiration. A cluster analysis on the model parameters was performed through an iterative relaxation of the objective performance to identify between species differentiation of inter-parameter relationships. Optimal parameter sets were used for initial landscape scale simulations. The results of cluster analysis are being used to refine the simulation model.

## Results

The response of water flux diurnally has many implications for coupling of land surface water flux to atmospheric conditions. Time lags between water flux and environmental conditions were highly variable and species dependent. In the coniferous species, there was no lag between  $J_S$  and  $D$  in red pine, white cedar and balsam fir in the forested wetland, while there was a half hour lag in balsam fir below the aspen canopy (Figure 2a). In the deciduous species, there was a half hour lag in aspen, an hour lag in sugar maple and basswood and an hour and a half lag in green alder between  $J_S$  and  $D$  (Figure 2a). All species were more correlated with  $Q$  that was occurring in the future and thus the correlation is considered spurious and is probably a result of the correlation between  $Q$  and  $D$ . Green alder is an exception that showed no lag with light (Figure 2b).

The lag between  $J_S$  and  $D$  can result from two different phenomena. First, the lag could be a result of low coupling between the leaves and the atmosphere. Stomata regulate leaf water potential to prevent runaway cavitation of conducting xylem. As  $D$  increases, stomata must close to maintain minimum water potentials. When leaves are not well coupled to the atmosphere, increases in  $D$  do not immediately result in increasing water flux and are thus not sensed at the stomata. Second, a lag could result from storage occurring above the sap flux measurement position. Because we found no effect of tree size on lag, and tree water storage is generally proportional to tree size, the lag between  $J_S$  and  $D$  is probably not related to water storage.

The large lag between  $J_S$  and  $D$  in green alder coupled with 0 lag between  $J_S$  and  $Q$  suggests that the stomata in green alder may be very insensitive to  $D$  and respond mostly to  $Q$ . We hypothesize that green alder may be extremely light limited. The combination of high nitrogen in the foliage of green alder due to its nitrogen fixing status, high water availability in the wetland, and understory status beneath white cedar and balsam fir result in alder having little need to strictly limit water loss with increasing  $D$  while existing in an extremely light limited environment.

Regardless of the mechanism behind the differential timing of  $J_S$  across the different species, the fact that there are differences in the timing of  $J_S$  has many significant implications. First, to determine the physiological response and appropriately model this response, we must account for the time response of  $J_S$  to  $D$  and  $Q$ . One way to further evaluate the time lags is to use branch measurements of sap flux because branches have very little water storage compared to the main stem measurements. A second and probably more important aspect of the differential timing of  $J_S$  is the effect on the coupling of surface processes to atmospheric processes.

In addition to the timing of water flux, the magnitude of water flux has many implications to land surface-atmospheric interactions. To evaluate this, we calculated cover-type transpiration using the following equation

$$E_C = J_s A_S : A_G$$

where  $E_C$  is canopy transpiration and  $A_S : A_G$  is sapwood area per unit ground area. For each cover type, we calculated  $E_C$  for each species and then summed up the transpiration for each day. The resulting daily  $E_C$  is shown in Figure 3 for each cover type. We found that only daily average vapor pressure deficit ( $D_z$ ) significantly explained the variation in daily  $E_C$ . In each cover type,  $E_C$  was best explained by an exponential saturation curve in response to  $D_z$ . The highest  $E_C$  in 2000 was found in aspen/fir averaging  $2.0 \text{ mm d}^{-1}$ . The conifer and forested wetland cover types each had an  $E_C$  averaging  $1.4 \text{ mm d}^{-1}$ . The lowest  $E_C$  was northern hardwoods averaging  $0.9 \text{ mm d}^{-1}$ . Surprisingly, leaf area index did not explain the changes in  $E_C$  rates among species. The low rates in northern hardwoods could be explained by a low canopy average stomatal conductance in sugar maple and basswood. Another possibility is that the thinnings that occurred in northern hardwoods stands approximately 10 years ago have resulted in a leaf area index that, while similar to the other cover types, is lower than the maximum for this cover type. This is born out by the large increase in sugar maple transpiration in 2001 compared with 2000. The high  $E_C$  in aspen fir is expected given the high growth rate of aspen and the resulting necessity to use large amounts of water through transpiration.

Shortly following leaf out in 2001 caterpillars defoliated the aspen. Following a three week period the aspen re-flushed their canopy, but with a smaller leaf area index and consequently a lower overall transpiration rate. The white cedar experienced a lowered water table height during 2001, which resulted in a reduced overall transpiration rate. Despite these changes in environmental conditions and transpiration fluxes, there was no significant difference in leaf water potentials between 2000 and 2001 (Figure 4). This result is important because it demonstrates that tree regulation of water potentials produces a simpler system, which will be exploited by models to scale up to larger regions.

Figure 5 shows transpiration scaled to the regional level compared to total evapotranspiration measured by eddy covariance at the WLEF 122m level. Scaled transpiration retains the exponential saturation response to VPD due to the overwhelming importance of well-coupled canopies in terms of relative area of the landscape. It is significant that the eddy covariance water flux also shows a similar limitation for most days shown. Also, the aspen transpiration rates are about equal to the tower flux, except at the high end of VPD. This provides further evidence that shifts towards greater aspen dominance in the region will have significant effects of water balance at the landscape level. Also important is the presence of forested wetland, which are not easily detected in remotely sensed data, and yet they contribute approximately half of the total water flux observed at WLEF. The significance of these results is that overall estimates of evapotranspiration by models may more closely approach actual flux values as a result of overestimation of transpiration. However, identification of forested wetland can help models more accurately capture total evapotranspiration fluxes, for the correct reasons. The results of this part of the study are reported in *Global Change Biology* and highlighted graphically on the front cover of the December 2002 issue (see image on the right).



Figure 6 shows model predicted transpiration compared against the sap flux stand-level estimates. The poor fit for red pine can be attributed to an increasing transpiration throughout the growing season as seen by the sap flux sensors, but which is currently not being captured by the model. A number of hypotheses for this increase are proposed including (1) warmer soil temperature and (2) increase in effective sapwood area. Leaf area index for red pine should not increase during mid-summer. Using Monte Carlo analysis we estimated predictive uncertainty of simulated transpiration from the landscape around WLEF (Figure 7). Red pine, aspen, and cedar show relatively strong sensitivity to VPD, maple shows moderate sensitivity, and basswood and alder show little adjustment in sensitivity with maximum stomatal conductance rates. The basswood has relatively large surface area leaves, which promote greater boundary layer resistance and hence lower coupling. Alder are low statured species with their feet in the water. They respond more to light, as shown in Figure 2.

We refined the results of the Monte Carlo analysis to mimic a boundary line analysis, which is used to determine reference canopy stomatal conductance ( $G_{Sref}$ ) and sensitivity of canopy stomatal conductance to VPD. We replicated with our model, hydraulic theory (Figure 8) in which the sensitivity of conductance to the log of vapor pressure deficit is linearly related to  $G_{Sref}$ . This result is consistent with the regulation of leaf water potential shown in Figure 4, which provides support for simplified models of canopy stomatal conductance for use with remote sensing driven models. These results are reported in Mackay *et al.* (2003b), and were extended in Mackay *et al.* (2003a) to estimate reference conductance from thermal remote sensing data. On the basis of this result we are teaming with the MODIS MOD16 team (evapotranspiration) to estimate reference and diurnal canopy stomatal conductance using estimates of VPD obtained from MODIS land surface temperatures.

## Conclusions

Our results show that there is a two-fold difference in the transpiration rate of forest cover-types in northern Wisconsin. In addition, there are large differences in the timing of water flux diurnally by species and cover type. Such large differences necessitate that regional water flux models must account for cover-type in order to accurately predict water fluxes in northern Wisconsin. Indeed, land managers are promoting aspen in many areas of northern Wisconsin in order to support a vigorous demand for pulp. Our results indicate that if the trend of promoting new aspen stands in lieu of northern hardwoods continues (J. Koch, Wisconsin Department of Natural Resources), it would drastically change the water budget of northern Wisconsin. Despite large differences in species flux rates and inter-annual variability of fluxes in response to environmental and management conditions, the strong controls on water potential demonstrated among our seven species shows that relatively simple models of transpiration may still be tractable. This is supported by our simulations, which show that simple models can reproduce the effect of these plant hydraulic controls on transpiration.

Our results further show that scaling up total evapotranspiration around WLEF required also knowledge of the extent of forest wetland, and the soil moisture and meteorological conditions of these wetlands. While these properties should be attainable with physically based hydrologic models, there remains work to be done in identifying forested wetland from remotely sensed data.

## Impacts

The results of our research point to significant impacts for diurnal land surface – atmosphere coupling and for landscape to global scale water and energy exchange:

1. Rapidly growing species such as aspen partition radiation into greater latent heat flux than slow growing species such as red pine and northern hardwoods. This is expected to have implications for spatial heterogeneity in PBL development and possibly mesoscale circulation and weather changes;
2. Forest management activities that promote rapidly growing species, such as aspen, will reduce groundwater recharge from expected levels for naturally growing species;
3. Leaf area index may not be key to scaling land surface fluxes in regional to global scale models of human altered ecosystems. The results of this research suggest that species differentiation is critical variable for making predictions of water, carbon, and energy fluxes from managed ecosystems.
4. Forested wetlands represent an important part of the hydrologic cycle in Boreal and other forested landscapes. The substantial fluxes from these sources need to be captured by models driven by remotely sensed inputs. Improvements to forest wetland classification are needed.
5. Inter-specific and inter-annual variability of transpiration fluxes can be easily incorporated into simple hydrologic models using linear relationships. This will greatly enhance water and energy flux calculations over large scales over forested landscapes.

## References

Burrows, S.N., S.T. Gower, M.K. Clayton, D.S. Mackay, D.E. Ahl, J.M. Norman, and G. Diak, 2002. Application of geostatistics to characterize LAI for flux towers to landscapes. *Ecosystems*, 5(7), 667-679.

### Refereed Publications - produced by this project

Mackay, D.S., S. Samanta, R.R. Nemani, and L.E. Band, 2003a. Multi-objective parameter estimation for simulating canopy transpiration in forested watersheds. *Journal of Hydrology*, 277(3-4), 230-247.

Samanta, S. and D.S. Mackay, 2003. Flexible automated parameterization of hydrologic models using fuzzy logic. *Water Resources Research*, 39(1), 1009, doi:10.1029/2002WR001349.

Mackay, D.S., D.E. Ahl, B.E. Ewers, S. Samanta, S.T. Gower, and S.N. Burrows, 2003b. Physiological tradeoffs in the parameterization of a model of canopy transpiration. *Advances in Water Resources*, 26(2), 179-194.

Mackay, D.S., S. Samanta, D.E. Ahl, B.E. Ewers, S.T. Gower, and S.N. Burrows. 2003c. Automated parameterization of land surface process models using fuzzy logic. *Transactions in GIS*, 7(1), 139-153.

Mackay, D.S., D.E. Ahl, B.E. Ewers, S.T. Gower, S.N. Burrows, S. Samanta, and K.J. Davis, 2002. Effects of aggregated classifications of forest composition on estimates of evapotranspiration in a northern Wisconsin forest. *Global Change Biology*, 8(12), 1253-1265. [Featured on the cover of the issue]

Ewers, B.E., D.S. Mackay, S.T. Gower, D.E. Ahl, S.N. Burrows, S. Samanta. 2002. Tree species effects on stand transpiration in northern Wisconsin. *Water Resources Research*, 38(7), 10.1029/2001WR000830.

Mackay, D.S., 2001. Evaluation of hydrologic equilibrium in a mountainous watershed: Incorporating forest canopy spatial adjustment to soil biogeochemical processes. *Advances in Water Resources*, 24(9-10), 1211-1227.

### Publications submitted or in progress – by this project

Ahl, D.E., S.T. Gower, D.S. Mackay, S.N. Burrows, J.M. Norman, and G. Diak, 2003a. Light use efficiency of a heterogeneous forest in northern Wisconsin: Implications for remote sensing and modeling net primary production. *Remote Sensing of Environment* (submitted).

Ewers, B.E., D.S. Mackay, S. Samanta, D.E. Ahl, S.N. Burrows, B. Cook, and K.J. Davis. 2003. Impact of leaf area dynamics on transpiration and canopy average stomatal conductance of seven tree species from northern Wisconsin. Tree physiology (in preparation).

Ahl, D.E., S.T. Gower, D.S. Mackay, S.N. Burrows, J.M. Norman, and G. Diak. 2003b. The effects of aggregated land cover data on estimating NPP in northern Wisconsin. *Remote Sensing of Environment* (Submitted).



Ahl, D.E., S.A. Ackerman, D.S. Mackay, S.T. Gower, and S.N. Burrows. 2003c. The effects of aerosol optical depth on vegetation indices: implications for modeling NPP in northern Wisconsin, USA. *IEEE Transactions on Geoscience and Remote Sensing* (Submitted).

#### **Theses produced from this project**

Douglas. E. Ahl. 2002. A measurement and modeling perspective on requirements for future remote sensing vegetation indices and classifications. Unpublished Ph.D., Environmental Monitoring Program, University of Wisconsin – Madison.

Samanta, S. 2001. Influence of event characteristics on predictive uncertainty of a hydrological model. Unpublished MS Thesis, Environmental Monitoring Program, University of Wisconsin – Madison.

Samanta, Sudeep. 2004 (anticipated). Adaptive parameterization of deterministic land surface simulation models under a fuzzy set framework, Department of Forest Ecology and Management, University of Wisconsin – Madison.

#### **Post-Docs Supported by this project**

Brent E. Ewers was supported primarily on this project for nearly three years. Immediately following his work on this project he accepted a tenure-track faculty position in the Department of Botany, University of Wyoming. Both Drs. Mackay and Gower continue to work with Dr. Ewers on separate projects.

## Graphics

The following figures were referenced in the text:

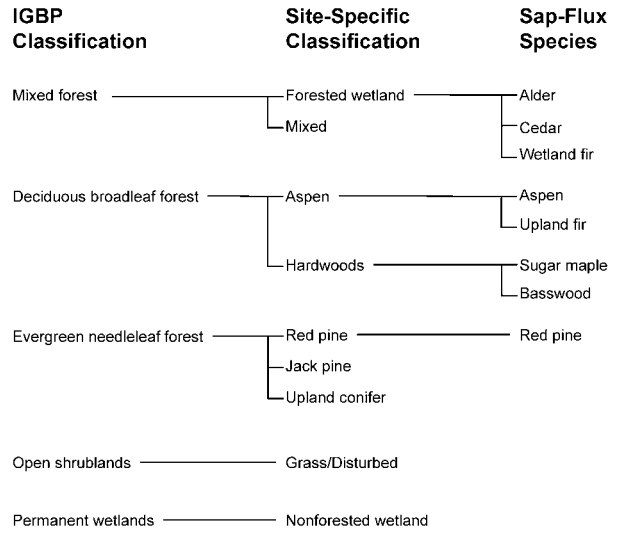
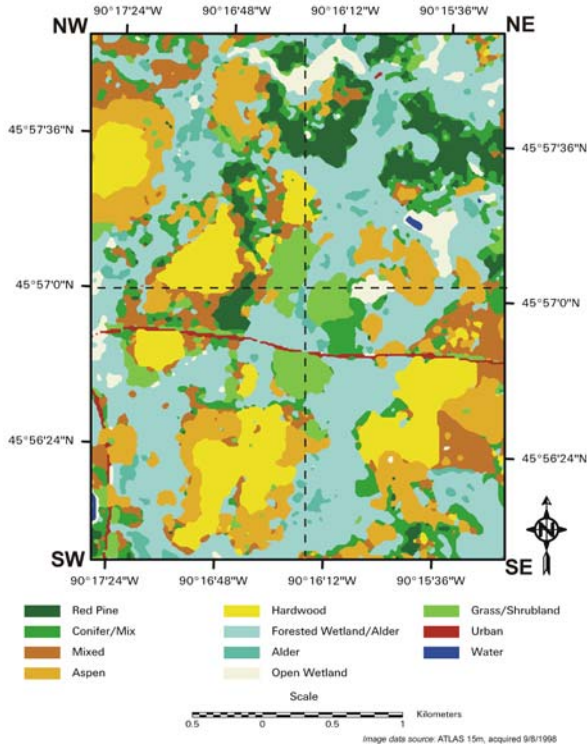


Figure 1. Site-specific forest cover map spanning the major species in the region around WLEF. A hierarchical classification was used to scale-up species information to IGBP classifications commonly used with MODIS and land surface models.

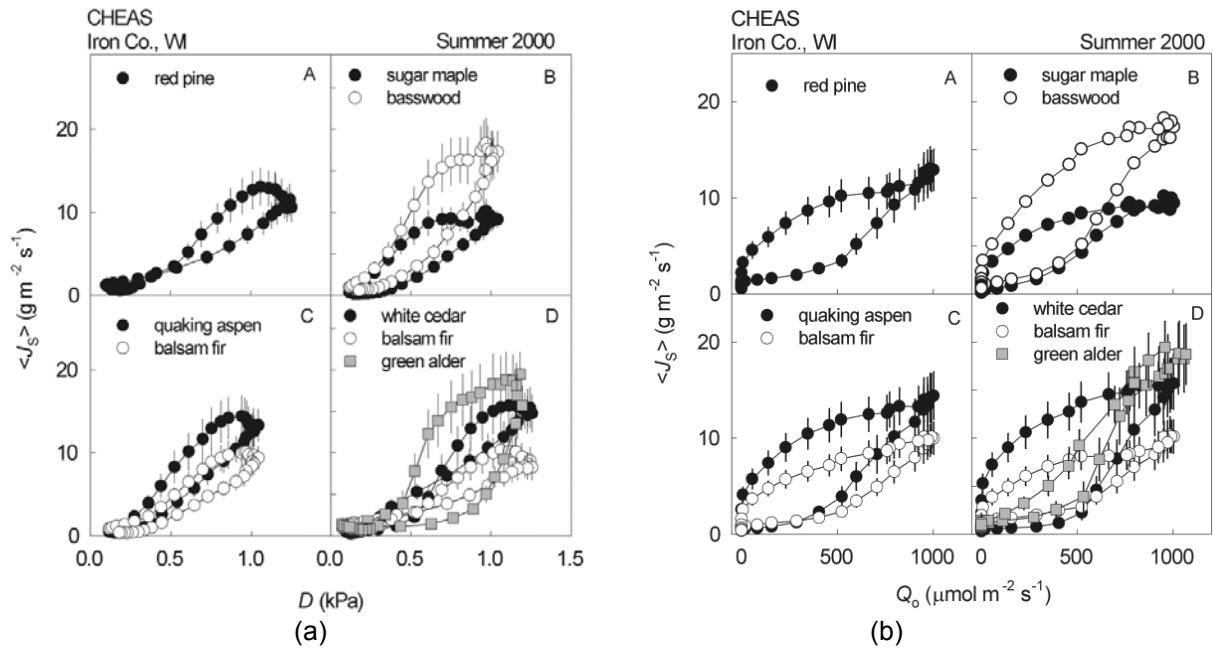


Figure 2. (a) Relationship between vapor pressure deficit ( $D$ ) and stem sap flux weighted by radial and circumferential trends ( $\langle J_S \rangle$ ) in four stands A) red pine, B) sugar maple/basswood, C) quaking aspen balsam fir, and D) white cedar/balsam fir/green alder. Each point represents the mean of 8 trees and bars are 1 SE. (b) Relationship between photosynthetically active radiation ( $Q$ ) and stem sap flux weighted by radial and circumferential trends ( $\langle J_S \rangle$ ) in four stands A) red pine, B) sugar maple/basswood, C) quaking aspen balsam fir, and D) white cedar/balsam fir/green alder. Each point represents the mean of 8 trees and bars are 1 SE.

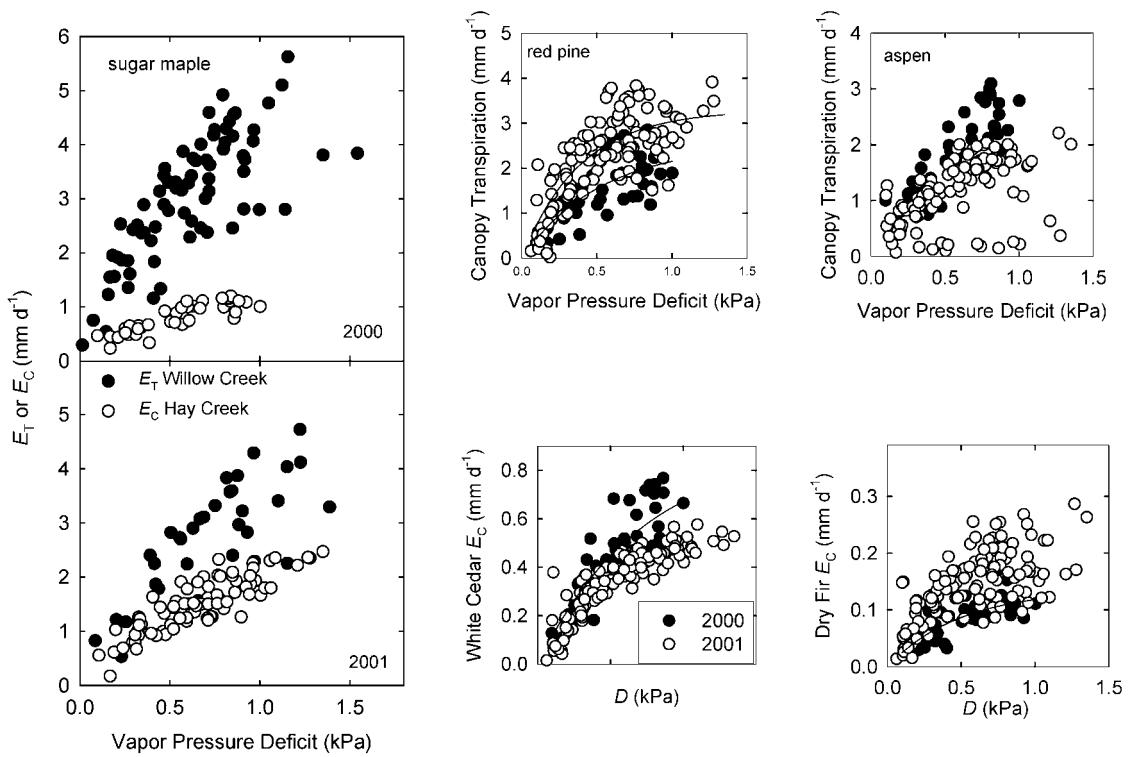


Figure 3. Inter-annual variability of sap flux among five major species. Sugar maple is shown at the NASA funded site (Hay Creek) and with eddy correlation at another site (Willow Creek). Sugar maple and red pine change because of leaf area index dynamics from thinning and drought, respectively. Aspen was defoliated in 2001 and did not recover to normal levels. Dry fir responded to increased light under the aspen canopy, and white cedar showed a decline associated with a drop in the water table.

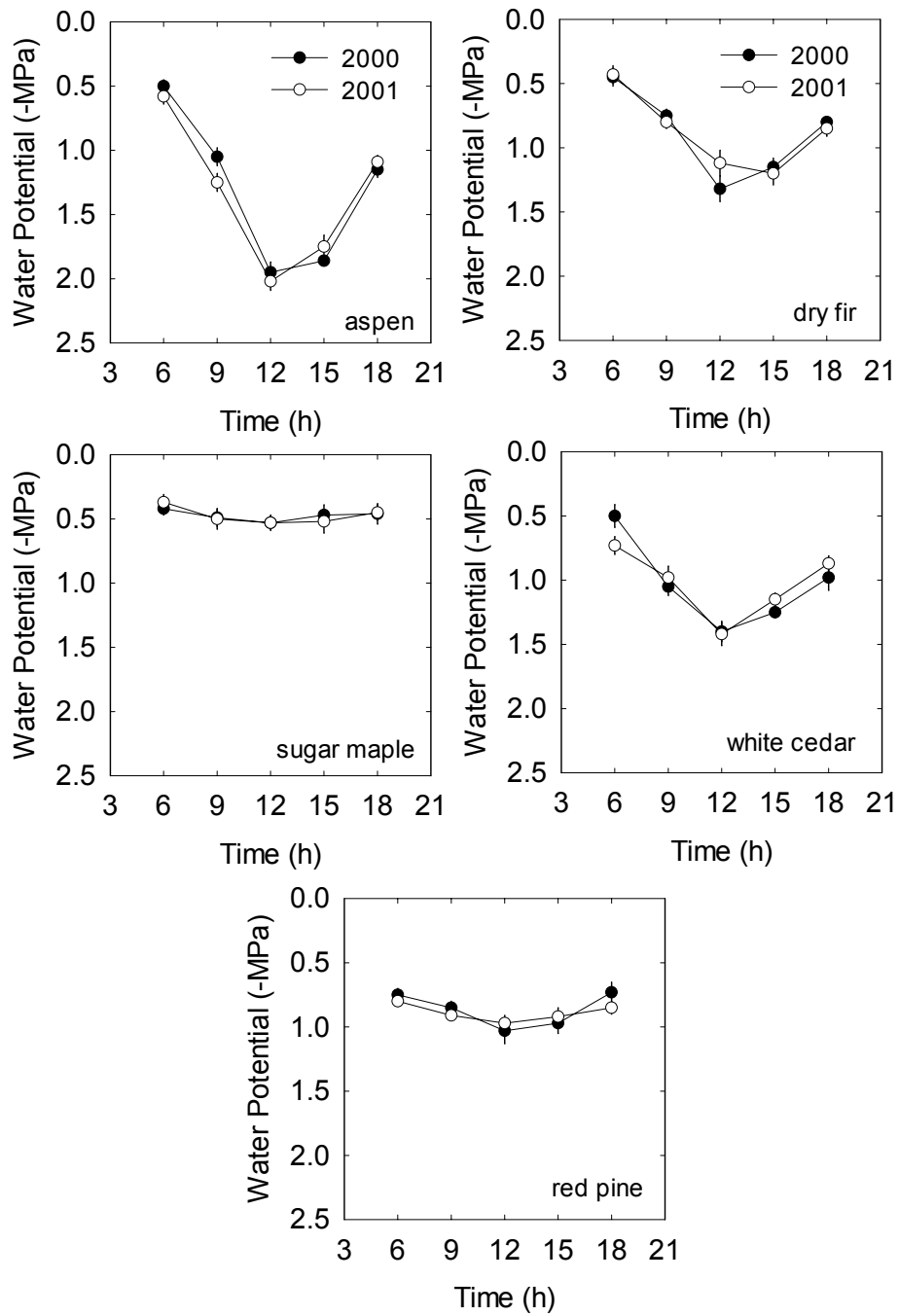


Figure 4. This shows leaf water potentials for five species for summer 2000 and 2001. Inter-annual differences in water potentials are not significantly different between the two years.

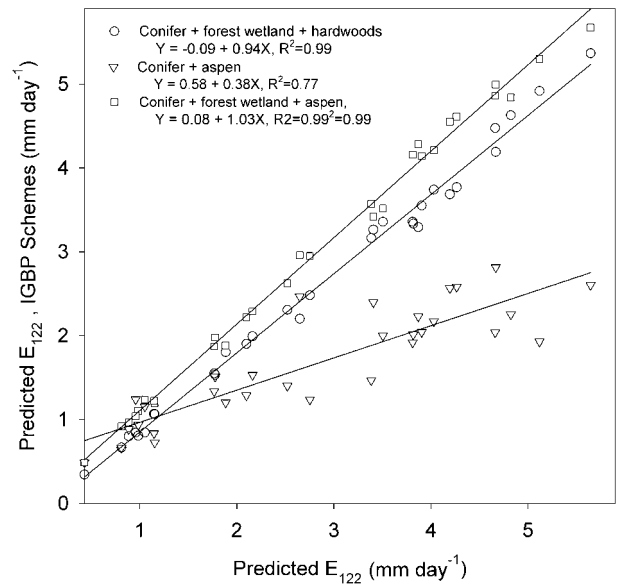
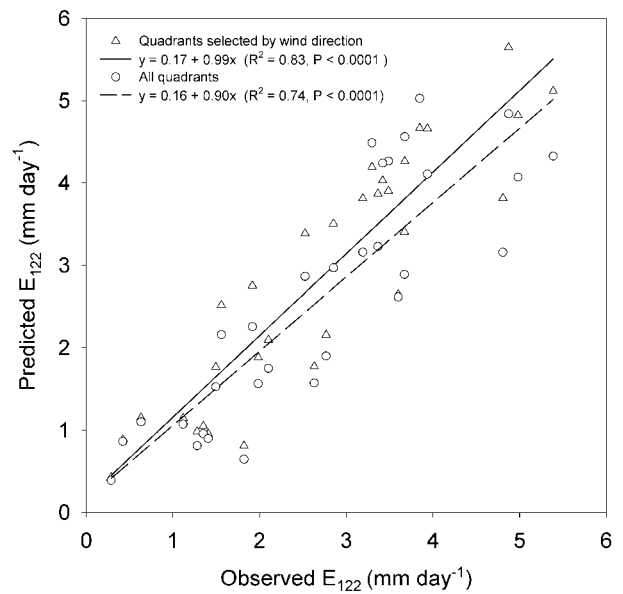
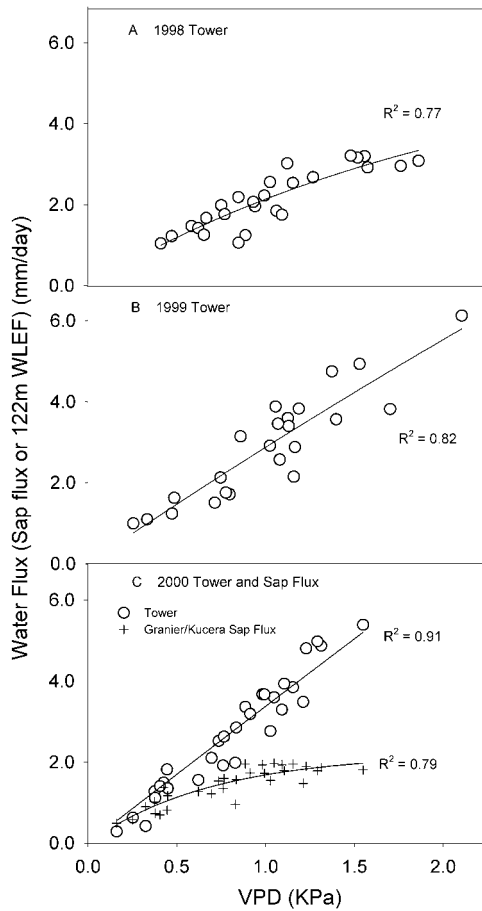


Figure 5. Total water flux at WLEF can be predicted from a combination of wetland soil water flux and sap flux transpiration. The region around the tower is well mixed with respect to water fluxes. Estimates of total evapotranspiration using biome-based models that ignore forested wetlands are under-predicted, although transpiration may be over-predicted.

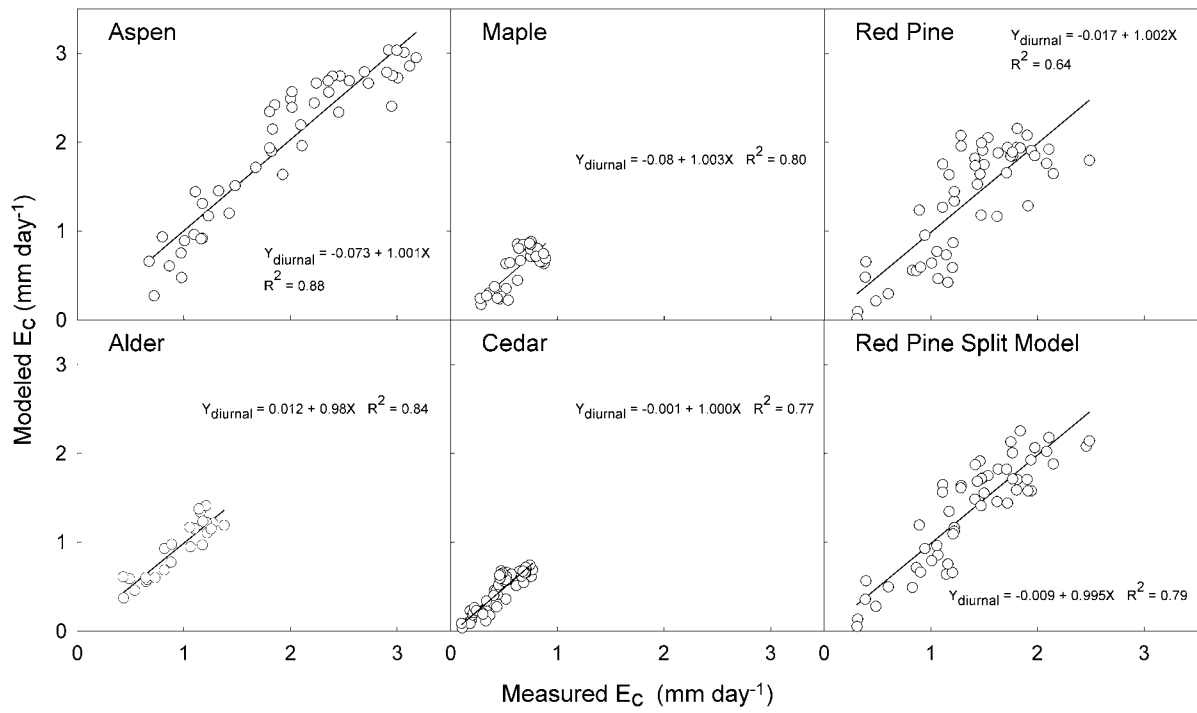


Figure 6. Simulated versus measured daily transpiration.

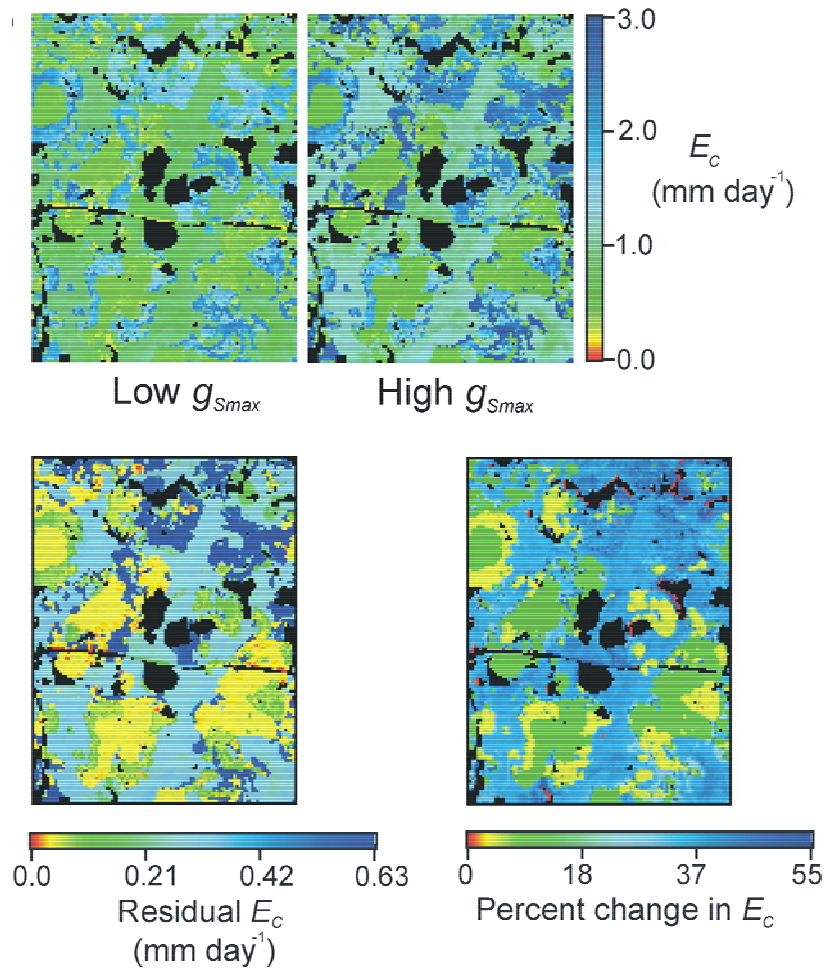


Figure 7. Simulated canopy transpiration for the 12.8-km<sup>2</sup> region around WLEF at TM resolution. The upper figures show results using low and high stomatal conductance parameters, based on the parameter selection and restriction. The difference between the two transpiration maps is the predictive uncertainty of not knowing which parameter values to select based on calibration without any physiological constraints.



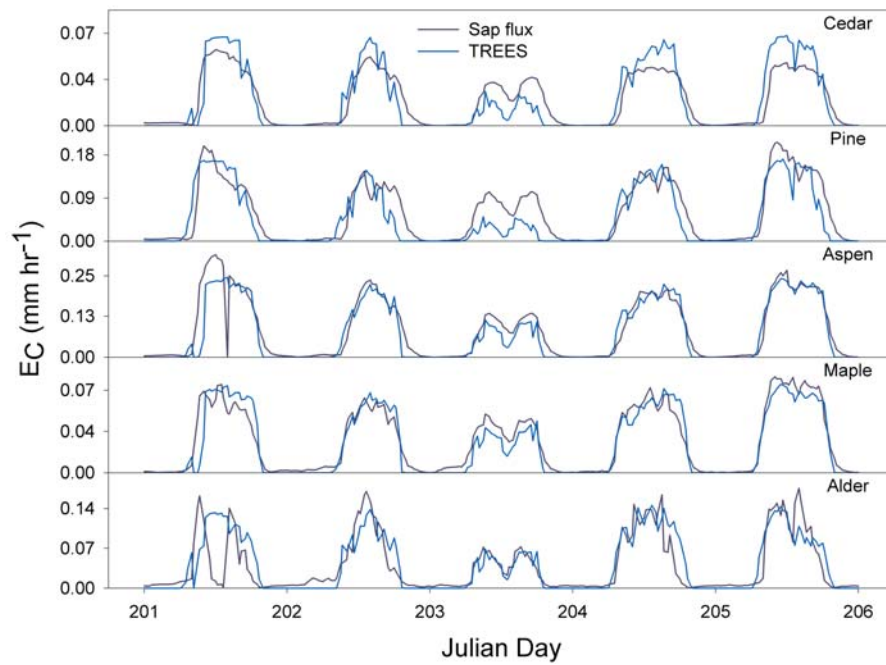
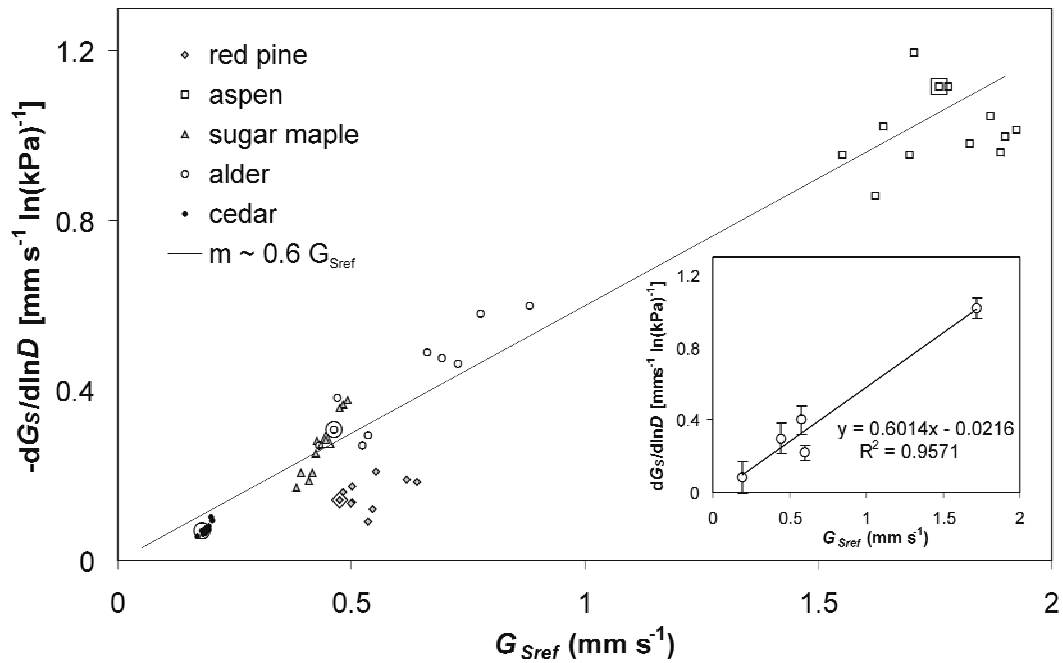


Figure 8. A selection and parameterization scheme was developed to assimilate physiologically meaningful parameters for the daily simulations of transpiration among different species (top figure). The bottom figure shows diurnal simulation results using these parameters without any additional calibration.

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