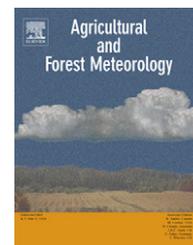


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Evapotranspiration estimates from eddy covariance towers and hydrologic modeling in managed forests in Northern Wisconsin, USA

G. Sun^{a,*}, A. Noormets^b, J. Chen^b, S.G. McNulty^a

^a Southern Global Change Program, USDA Forest Service, Raleigh, NC 27606, United States

^b Department of Environmental Sciences, University of Toledo, Ohio 43606, United States

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ABSTRACT

Direct measurement of ecosystem evapotranspiration by the eddy covariance method and simulation modeling were employed to quantify the growing season (May–October) evapotranspiration (ET) of eight forest ecosystems representing a management gradient in dominant forest types and age classes in the Upper Great Lakes Region from 2002 to 2003. We measured net exchange of water vapor fluxes in a 63-year-old mature hardwood (MHW) stand, a 60-year-old mature red pine (MRP) stand, a 3-year-old young hardwood (YHW) stand, a 17-year-old intermediate hardwood (IHW) stand, a young red pine (YRP age 8) stand, an intermediate red pine (IRP age 21) stand, and two pine barren ecosystems burned 12 years (PB1) and 2 years (PB2) ago. Field data suggested that there were no significant differences in growing season (June–September) ET/precipitation ratio among all ecosystems in 2002. However, PB2 had significantly lower ET/precipitation than those of other ecosystems in 2003. The ratios were much higher for all ecosystems, up to 0.90 for IHW, during the peak summer months (June–July). PB2 was the lowest (0.64) during that period. Stand leaf area index alone did not explain ecosystem ET at the landscape scale. Seasonal ET values measured by the eddy covariance method were significantly lower than those simulated with a process-based hydrologic model, MIKE SHE. Our integration approach combined with field measurements and simulation modeling proved to be useful in providing a full picture of the effects of forest cover type change on landscape scale water balance at multiple temporal scales. The ET procedure used in the MIKE SHE model needs improvement to fully account for the effects of vapor pressure deficit on tree transpiration. Seasonal distributions of ET coincided with precipitation in the growing season, when fluxes estimated by both field and models were the highest. The simulation model suggests that removal of conifer forests in the study region may reduce ET immediately by 113–30 mm/year or about 20%, but our field data suggests that ET can recover within 8–25 years from re-growth of hardwood forests.

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1. Introduction

Century-long studies of the forest–water relations in the Lake States region (Verry, 1986; Mackay et al., 2002; Ewers et al., 2002)

and elsewhere in the United States (Ice and Stednick, 2004) and around the world (Andreassian, 2004) have shown that forest management plays a great role in regulating the hydrological cycle, such as streamflow and evapotranspiration, at multiple

* Corresponding author. Tel.: +1 919 515 9498; fax: +1 919 513 2978.

E-mail address: Ge_Sun@ncsu.edu (G. Sun).

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temporal and spatial scales by altering ecosystem water balances. However, hydrologic responses to land management and cover change vary greatly because of the complex interactions among climate, soil, and vegetation from individual tree to landscape scales (Andreassian, 2004; Ewers et al., 2002; Mackay et al., 2002).

The Midwest United States has experienced one of the largest land use changes in the world. It has been estimated that 137 million acres of virgin forest in this region was converted to agriculture and urban uses between the 1620s and 1990s (Verry, 2004). The remaining forests are highly fragmented. For example, the Chequamegon-Nicolet National Forest in Northern Wisconsin, an area of approximately 325,000 ha, was logged, mainly for pine, from 1860 to 1920, and the forest has been regrown for the past 85 years (Bresee et al., 2004). The consequences of this large-scale forest change on water balances have not been studied in detail. In the Lake States, clearcutting upland hardwoods or conifers could increase annual streamflow by 90–200 mm/year (≈ 30 –80% increase). Yet a similar forest management practice would have minor hydrologic effect on peatlands (Verry, 1986). To empirically investigate changes in values of key hydrological variables and identify potential biophysical drivers, process-based studies were conducted at tree species, stand, and landscape levels in forests of Northern Wisconsin to directly measure sapflow (Ewers et al., 2002; Mackay et al., 2002), and water and carbon fluxes using eddy flux towers (Baldocchi et al., 1996). These studies reported more than twofold differences in evapotranspiration (ET) among the dominant forests in the region (i.e., northern hardwoods, red pine/Jack pine, aspen/fir, and forested wetlands), primarily due to differences in total sapwood area and tree hydraulic conductance and a much lesser extent to differences in total leaf area. These studies further suggested that forested wetlands had significantly higher total ET than uplands, calling for physically based hydrologic models for more accurately estimating soil evaporation water fluxes in the region. Similar effects of forest changes on water balances were also reported for the Southern USA. Swank et al. (1988) found that clearcutting a southern hardwoods forest in the Appalachian Mountains in western North Carolina could result in a 200–400 mm/year increase in water yield, mostly because of reduction in ecosystem ET. In contrast, clearing of the slash pine (*Pinus elliottii*) forests on flatwoods in north Florida had limited and short-term effects on ET, and thus water yield, especially during wet periods (Gholz and Clark, 2002; Bliss and Comerford, 2002; Sun et al., 1998).

Recently, concern about global climate change has led researchers in forest hydrology to look more closely at connections between the water and nutrient cycles and the dynamics of energy and carbon cycles (McNulty et al., 1997; Sun et al., 2000; Schafer et al., 2002). Accumulated field data (Wilson et al., 2002) and meso-scale simulations (Werth and Avissar, 2002) suggest that land surface characteristics at the landscape scale affect water and energy partitioning and that land–atmosphere feedbacks can be manifested at large scales (Pielke et al., 1998). Scaling up stand-level flux measurements to landscape scales (the bottom-up approach) remains a theoretical challenge because ecosystem functions and responses to disturbances at the regional scale do not equal

the sum of individual ecosystem functions and responses (Chen et al., 2004). Studies that quantify and contrast water balances of multiple, dominant ecosystems of a landscape are critically important as a basis for modeling land–atmosphere interactions at broader scales.

At the watershed scale, ET represents the largest water flux next to precipitation, but it is the most challenging variable to measure at this scale due to the heterogeneity of the landscape. In practice, ET is often calculated as the residual from precipitation and other water fluxes (e.g., runoff, change in soil water storage) and is subject to large errors at a short temporal scale and in watersheds with poorly defined surface and subsurface watershed boundaries. The energy balance method and eddy covariance technique provide alternative measures of latent heat flux, equivalent to ET, and offer promising estimates for closing the water balances of ecosystems (Wilson et al., 2001; Law et al., 2002). Meanwhile, water flux measured at shorter temporal scales has been scaled up to construct annual water budgets at ecosystem scale (Gholz and Clark, 2002; Thornton et al., 2002; Mackay et al., 2002; Ewers et al., 2002). The ET data collected at eddy flux towers have been widely used for validating traditional hydrologic models to extrapolate findings at individual sites to the regional scale (Wilson et al., 2001).

This paper examines measured ET from several eddy flux towers in forest ecosystems along a management gradient in the Chequamegon-Nicolet National Forest in Northern Wisconsin and evaluated modeled ET using a biophysically based integrated forest hydrologic model, MIKE SHE (DHI, 2004). We hypothesized that: (1) coniferous forests have higher ET than hardwood forests because the former can lose water through interception and transpiration during non-growing seasons; (2) the ET of mature forests is higher than that of young forests because mature forests have more leaf area (i.e., ET is age-dependent) (Chen et al., 2002). Specifically, our study objectives were to: (1) compare ET changes over time in multiple ecosystems; (2) evaluate the effect of forest age on ET; (3) simulate changes of ET using a hydrological model to expand our capability to predict ET for the dominant ecosystems of the region.

2. Materials and methods

2.1. Study sites

The study sites (46°30′–46°45′N, 91°2′–91°22′W) were located in the Chequamegon-Nicolet National Forest, in Ashland County in Northern Wisconsin, USA (Fig. 1). The landscape is generally flat and homogeneous. The predominant soils are well-drained loamy tills with ground moraine, non-calcareous sandy loamy tills, and outwash sand. Sandy loams are found below 30 cm from the ground surface, and the groundwater table was at depths greater than 2 m in the uplands, but was at the surface in wetland areas (Ewers et al., 2002). The climate is humid-continental with average temperature ranging from -13°C in January to 20°C in July, and averaged annual precipitation varies between 600 and 900 mm with 70% of this occurring during the May–October growing season. Annual long-term ET in the region is 560 mm or 70% of annual

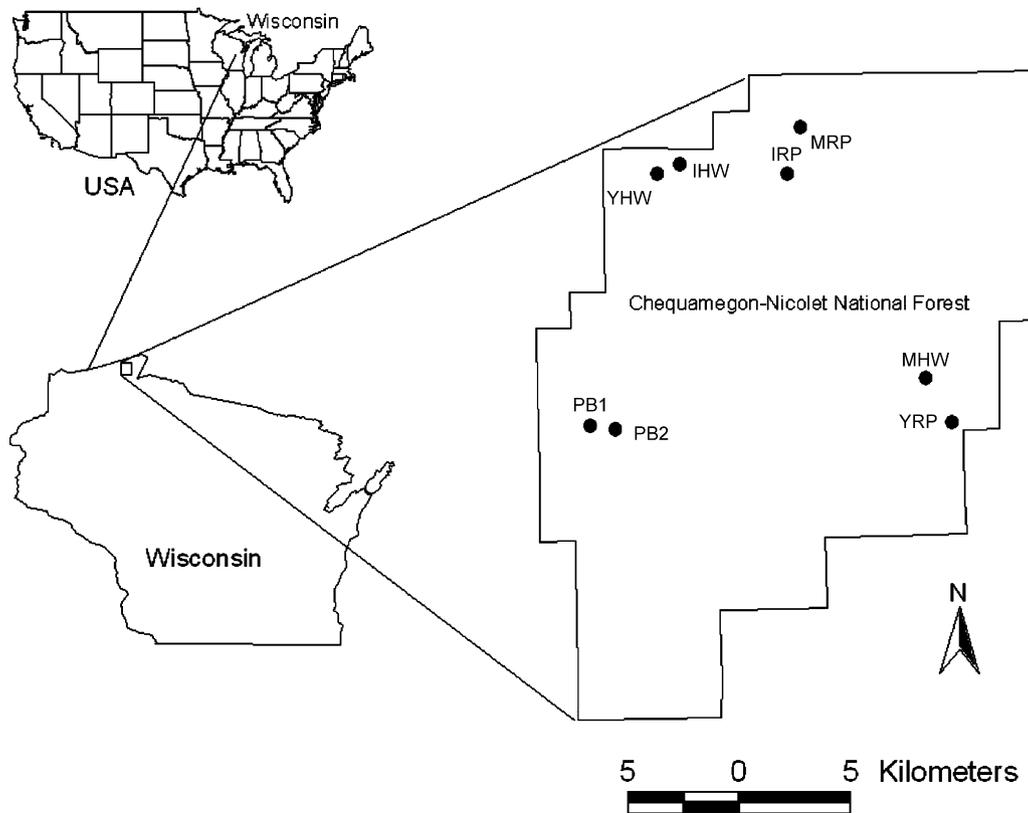


Fig. 1 – Eddy covariance tower locations in the Chequamegon-Nicolet National Forest in Northern Wisconsin, USA.

precipitation as estimated from long-term hydrology (1951–1980) and climatic records (Gerbert et al., 1987; Daly et al., 2000). The vegetation is dominated by second-growth hardwoods (40–45%) and conifer stands including red pine (*Pinus resinosa*) and jack pine (*Pinus banksiana*) plantations (35%), and pine barrens (17%) (Bresee et al., 2004).

We selected multiple ecosystems for this 2-year study to investigate how these ecosystems respond to land disturbance and environmental variability at the landscape scale. The ecosystem types included mature hardwoods (MHW) dominated by aspen-birch (*Populus grandidentata*, *P. tremuloides*, *Betula papyrifera*), mature red pine (MRP), naturally regenerated young hardwoods (clearcut in 2000) (YHW), young red pine (8-year old), intermediate hardwoods (17-year old), intermediate red pine IRP (21-year old), a natural pine barren (PB1), and a burned pine barren (PB2). Pine barrens are a temperate savanna community dominated by scattered jack pines, oaks (*Quercus* spp.), shrubby hazelnuts (*Corylus* spp.) and prairie willow (*Salix humilis*), and herbs (Bresee et al., 2004). Leaf area index (LAI) was estimated by hemispheric photography and the WinScanopy image analysis program (Regent Instruments, Quebec, Canada). Forest community characteristics and experimental and modeling designs for the two experimental years, 2002 and 2003, are presented in Table 1.

2.2. Micrometeorological measurements

Meteorological measurements at a 30 min resolution were initiated in January 2002. Our data analysis included data

collected between 1 January 2002 and 31 December 2003. Net radiation (R_n , $W m^{-2}$) above the stand canopy was measured with a Q7.1 net radiometer (radiation and energy balance systems, REBS, Seattle, WA, USA) and air temperature (T_a , °C) and relative humidity (%) were measured above, within, and below the canopy (1.8 m) using HMP45AC probes (Vaisala, Finland). Soil temperature (°C) and matric potential (bars) were measured at a 30 cm depth using CS107 temperature probes and CS257 gypsum moisture blocks (SCI, Logan, UT, USA). Precipitation (mm) was measured with a tipping bucket rain gauge (SCI) located at a permanent weather station 8–25 km from the individual stands. The daily values were derived from these 30 min raw data. When daily air temperature and precipitation data were not available due to equipment failure, manual measurements at the University of Wisconsin Ashland Agricultural Research Station were used.

2.3. Net exchange of energy and water vapor

Net exchange of energy and water vapor was measured continuously in five ecosystems (MHW, MRP, YHW, YRP and PB1) in 2002 and five ecosystems (MHW, MRP, IHW, IRP and PB2) in 2003, a total of eight different year types of ecosystems, by employing the eddy covariance method. Each system included a Li-7500 open-path infrared gas analyzer (IRGA, Li-Cor), a CSAT3 three-dimensional sonic anemometer (CSI), a CR5000 datalogger (CSI), and a barometer (CS105, CSI). The 30 min mean latent heat flux was calculated after screening the data for periods of precipitation, instrument or power

Table 1 – Stand characteristics and experimental design of seven forest ecosystems across a management gradient in the Chequamegon-Nicolet National Forest, Wisconsin, USA

Ecosystem	Age (years) in 2002	Canopy cover (%)	Basal area (m ² ha ⁻¹)	Maximum leaf area index	Measurement/modeling periods
Mature hardwood (MHW)	65	97	29.1	4.0	2002, 2003 simulation applied
Mature red pine (MRP)	63	70	13.5	2.8	2002, 2003 simulation applied
Young hardwood (YHW)	3	2	1.5	0.5	2002 simulation applied
Young red pine (YRP)	8	17	4.6	0.52–0.93	2002
Pine barrens (PB1)	12	4	0.5	0.2	2002 simulation applied
Pine barrens (burned) (PB2)	2	0	0.0	0.05	2003
Intermediate hardwood (IHW)	17	N/A	N/A	~3	2003
Intermediate pine (IRP)	21	N/A	N/A	~3	2003

failure, low turbulence conditions, and out-of-range records. Turbulent exchange of water vapor and energy were calculated according to Leuning (2004) using two-axis coordinate rotation. Sonic temperature was corrected according to Schotanus and Nieuwstadt (1983), and the fluxes were corrected for fluctuations in air density using the Webb–Pearman–Leuning expression (Webb et al., 1980). Data quality was assessed using the stationarity and stability criteria (Foken and Wichura, 1996), along with range and variance checks. Energy balance closure was 56–68% (Nan Lv unpublished personal communication) and was not used for data screening. Wind characteristics and turbulent fluxes did not show detectable directional variation, and therefore fluxes from behind the sensor were not explicitly removed, but subjected to the standard screening described above. The 30 min average of latent heat was further summed to a daily scale. Latent heat fluxes for periods when the sensors were wet were rejected. We also discarded some daily latent heat data when the values were abnormally higher than those of net radiation. Daily ET in mm day⁻¹ was derived by dividing the LE by the vaporization constant.

2.4. Water balance modeling

We employed the physical forest hydrologic model MIKE SHE (Abbott et al., 1986a,b; DHI, 2004; Tague et al., 2004; Im et al., 2004) to estimate daily ET for 2002 and 2003 for three major contrasting forest ecosystems where field data over the 2-year-study period were available. These ecosystems were mature red pine (MRP), mature hardwoods (MHW), and two pine barrens with different burn history (PB1 and PB2). The MIKE SHE model simulates the full hydrologic cycle characteristic of a forest ecosystem, including ET (i.e., sum of canopy interception, plan transpiration, and soil evaporation) and vertical soil water movement in the unsaturated soil zone to the groundwater. A brief description of the modeling procedures and mathematical formulation are provided below. Further details can be found in the model use manual (DHI, 2004) and associated publications (Abbott et al., 1986a,b; Tague et al., 2004; Im et al., 2004).

One of the important components of the MIKE SHE model is the ET submodel that interacts with atmospheric demand, soil moisture content, and groundwater table dynamics. As in most physically based hydrologic models, total ET flux is controlled by potential evapotranspiration (PET) which is defined as maximum ecosystem ET under no-water-stress conditions. Several models are available to estimate this

variable (Lu et al., 2005). In this study, we computed PET externally by Hamon's method (Federer and Lash, 1978; Lu et al., 2005) before running the hydrologic model. Daily Hamon's PET was computed as a function of measured air temperature and calculated daytime length using site location (latitude) and date (Julian Day).

$$P_{ET} = 0.1651DV_d k \quad (1)$$

where P_{ET} is potential evapotranspiration (mm day⁻¹), D the time from sunrise to sunset in multiples of 12 h, computed as a function of date, latitude, and slope and aspect of the watershed; V_d the saturated vapor density (g m⁻³) at the daily mean temperature, T (°C) = 216.7 $V_s/(T + 273.3)$; V_s the saturated vapor pressure (mbar) = 6.108 × exp[17.26939 $T/(T + 237.3)$]; and k is the correction coefficient (1.1) to adjust PET calculated using Hamon's method to measured values.

Water loss through canopy interception (E_c) was modeled as a function of daily PET and daily leaf area index LAI (denoted as L below):

$$E_c = \min(I_{max}, P_{ET}) \quad (2)$$

$$I_{max} = C_{int}L \quad (3)$$

where I_{max} is maximum canopy interception storage, which must be filled before stemflow occurs. C_{int} is an interception coefficient with a typical value of 0.05 mm.

Plant transpiration (T) was described as a function of PET, L , root distribution, and soil moisture content in the rooting zone:

$$T = f_1(L) f_2(\theta) R P_{ET} \quad (4)$$

where f_1 and f_2 , are empirical functions of LAI, and soil moisture content (θ) in the rooting zone and PET, respectively. R is a root distribution function that allows water to be extracted at varying soil depths over time.

Soil evaporation, as the last ET component, was simulated as a function of P_{ET} , L , soil moisture, and residual energy availability ($P_{ET} - T$):

$$E_s = P_{ET} f_3(\theta) + (P_{ET} - T - P_{ET} f_3(\theta)) f_4(\theta) (1 - f_1(L)) \quad (5)$$

where f_3 and f_4 are empirical functions of soil moisture content.

We assumed a flat land surface, no surface flow, and no net lateral groundwater flow in each of the forest ecosystems. We

used generalized soil and vegetation parameters for the study sites, but applied the measured daily climatic variables (air temperature and rainfall) in this study. The default parameters for the soil moisture release curves and hydraulic conductivity for sandy loam soils were used. The model was not calibrated because we did not intend to fit the model to the specific site conditions, but rather to estimate the potential errors in modeling by comparing simulation results with the eddy flux measurements. We hope to use the information gained to predict ET for other ecosystems in the region. In the simulation runs we focused on three ecosystems that represent a mature hardwood forest (Max LAI = 4.0), a mature red pine forest (Max LAI = 2.8), and PB1 and PB2 systems with low LAI (Max LAI = 0.5 and 0.05, respectively). Model input and output (Table 2) are provided to give a general overview of model requirements and functions. Detailed model description, structure, and algorithms are found in the MIKE SHE user's guide (DHI, 2004) and Abbott et al. (1986a,b). Analysis of variance (ANOVA) was performed to examine the differences among ecosystems.

3. Results

Although forest evapotranspiration is relatively stable in comparison with other components of the water balance, it is closely related to soil water availability as determined by precipitation, runoff, and atmospheric demand. The monthly rainfall distribution in 2002 was similar to the 30-year average except in October, which was wetter than average (Fig. 2). The year 2003 was drier than 2002 and the long-term average except during May, September, and October. Because the soil infiltration capacity was high, our study sites did not have any noticeable surface runoff. However, slow internal subsurface drainage was expected to occur beneath the low-relief landscape.

In general, daily ET for each of the ecosystem varied greatly during the growing seasons (May–October) (Fig. 3). The large day-to-day variability (>3–5-fold) in the summer months suggests a complex control on the ET processes. ET peaked much earlier and higher in 2003 (Mid-July) than in 2002 (end of July) (Fig. 3). Because many ET data points for May and October were missing or unusable, the ET data for May and October were not used in the cross-site comparisons in this study. Instead, we focused on ET comparison for the June–September

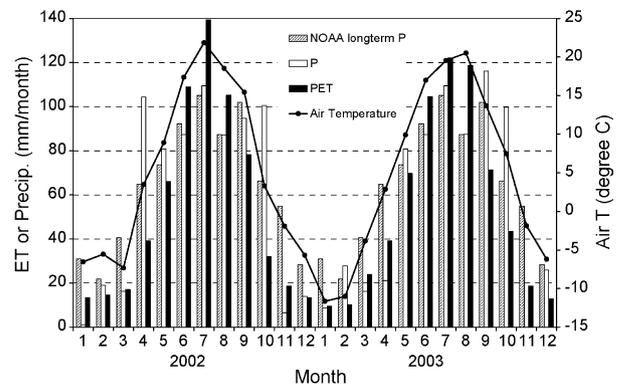


Fig. 2 – Monthly precipitation, potential evapotranspiration, and air temperature patterns during 2002 and 2003 at the study site in North Wisconsin.

periods when the data were most complete for both years. The ANOVA at the daily temporal scale indicated that there were no significant ecosystem-to-ecosystem differences ($p < 0.05$) in ET among the five ecosystems in 2002. However, there were significant ecosystem-to-ecosystem differences ($p < 0.01$) in 2003. Daily ET at the PB2 site was significantly lower than that at the other four sites (MHW, MRP, IHW and IRP) (Fig. 3, Table 3). Values of ET for the other four ecosystems did not differ significantly ($p = 0.05$). Linear regression analysis suggested that LAI was not significantly correlated with averaged daily ET of the five ecosystems in 2002 ($R^2 = 0.0$). However, the correlation between LAI and measured ET for the five ecosystems was significant ($R^2 = 0.96$) in 2003 although there were no significant correlations among the four ecosystems (MRP, MHW, IHW and IRP). The correlation between ET and LAI was heavily influenced by the PB1 and PB2 sites. Without data for these two sites, LAI was not effective in explaining the variation in ET among ecosystems.

Two examples of diurnal variation in dry canopy ET for 2002 and 2003 are given in Fig. 4 to show how the ecosystems differed on an hourly basis. For example, it appeared that red pines (MRP and YRP) had higher ET than the hardwoods (MHW and YHW) in September 2002, while daytime ET for PB1 differed little from that for the rest of the ecosystems at that time (Fig. 4a). ET was much greater on 18 July 2003, than on 11 September 2002 (Fig. 4b). However, there were no differences

Table 2 – Major model inputs and outputs of the hydrologic model, MIKE SHE

Model overview		Variables and parameters
Input requirements	Climate	Daily precipitation, air temperature for estimating potential evapotranspiration calculated using Hamon's method (Federer and Lash, 1978)
	Vegetation	Effective rooting depth (60 cm); daily leaf area index (LAI) estimated from literature and field observation
	Soils	Hydraulic conductivity and soil moisture release curve for sandy loams (Van Genuchten et al., 1991)
Output	Daily canopy interception, transpiration, soil evaporation, soil moisture content (%) at different depths, groundwater table depth, soil water drainage from the rooting zone	

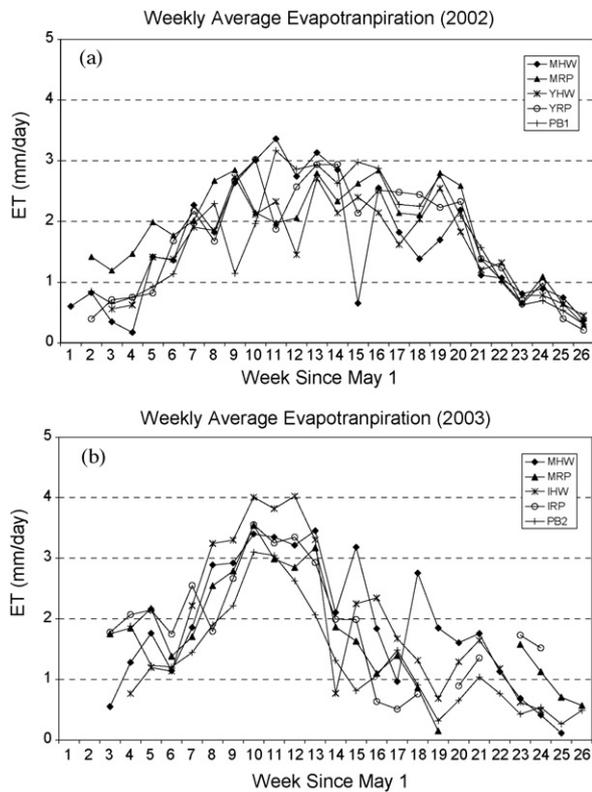


Fig. 3 – Measured daily ET by the eddy covariance method for: (a) mature hardwood (MHW), mature red pine (MRP), recently clearcut hardwoods (YHW), young red pine (YRP), and pine barrens (PB1) during 2002; (b) mature hardwood (MHW), mature red pine (MRP), intermediate red pine (IRP), intermediate hardwoods (YHW), and burned pine barrens (PB2) during 2003.

in ET among MRP, IRP, and MHW on 18 July 2003. The largest difference in ET occurred between IHW and PB2 on 18 July 2003. The rest of the ecosystems had similar ET on this particular day. The ET comparison for these two dates further suggested that the relative magnitude of ET fluxes among ecosystems had large variability.

Comparisons of peak ET values for the two summer months (June–July) which had almost complete data showed a different contrasting pattern. There were no significant differences in ET ($p = 0.05$) among the five ecosystems with diverse tree LAI ranging from 0.5 (YHW) to 4.0 (MHW). ANOVA suggested that there were significant differences in daily ET ($p < 0.01$) among the five ecosystems measured in 2003. PB2 had the lowest average daily ET ($2.1 \pm 0.9 \text{ mm day}^{-1}$), and the ET values for the other four ecosystems did not differ significantly in 2003.

Monthly (June–September) ET comparisons across ecosystems for 2002 showed that MRP had the highest ET during the early growing season (May), but that ET for the MHW site was the highest during the peak month of July (Fig. 5). Monthly ET values for PB1, YHW, and YRP, which had low leaf areas, were found to be comparable to those for the mature systems during June, but 10–24 mm lower than July ET for MHW. Similar contrasting patterns were found for July 2003, when all

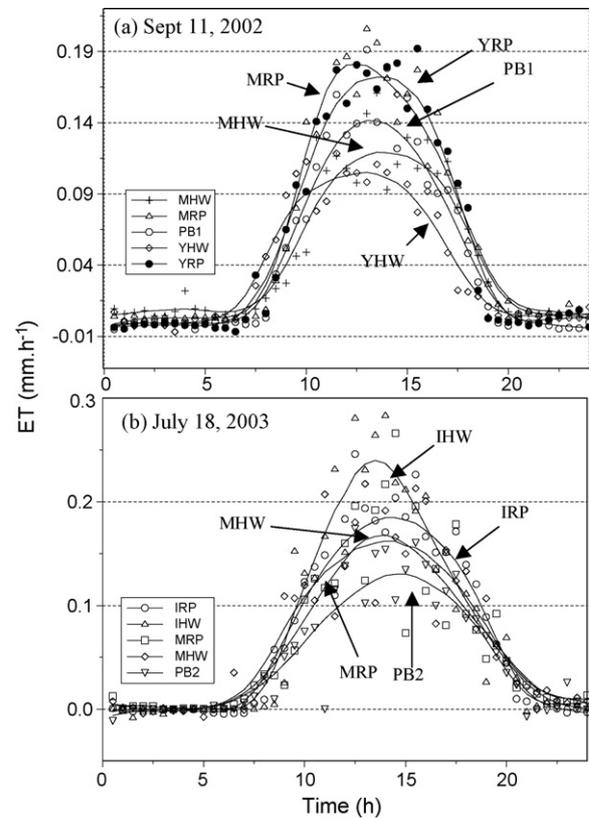


Fig. 4 – Diurnal change of ET for: (a) 11 September 2002 and (b) 16 July 2003.

sites had a much higher ET than in 2002 (Fig. 5). Except in May and September, PB2 had the lowest monthly ET throughout 2003. The fact that July ET was notably higher in 2003 than in 2002 for all sites suggests a significant water stress in July 2002. Precipitation was 110 mm in each year, but the July precipitation was 30 mm below PET in 2002 and the air temperature was 2°C higher in 2002 than in 2003 (Fig. 2). Soil moisture measurements confirmed this observation. For example, measured daily ET for the MHW ecosystem in July 2002 was $3.0 \pm 1.1 \text{ mm}$ (mean \pm 1 S.D.) and the soil matric potential at the 30 cm soil depth was $1.1 \pm 0.98 \text{ bars}$, while ET and soil potential were measured as $4.4 \pm 2.8 \text{ mm}$ and $0.42 \pm 0.34 \text{ bars}$, respectively, in July 2003. Our hydrological simulation model indeed suggested a severe soil moisture stress during the summer months for both years (see later discussion). In contrast, measured ET in August 2002 was lower than that in 2003 (Fig. 5), presumably because the PET was 14 mm lower and the mean temperature was 2°C lower than that in 2003 (Fig. 2). The simulation model did not show apparent water stress in August for either year.

During the growing season from June to September, ET accounted for $\approx 60\%$ (PB1) to 70% (MRP) of precipitation in 2002, and for 45% (PB2) to 70% (MHW) in 2003. As expected, the ET/P ratios were higher in June and July than the growing season average, because ET was highest during these months. ET/P ratios ranged from 62% (YHW) to 75% (MHW) in June–July in 2002 and 64% (PB2) to 90% (IHW) in 2003 (Table 3). ET was the lowest in stands with low leaf area (PB1, PB2 and YHW), but

Table 3 – Summary of daily evapotranspiration (ET) across the eight ecosystems during the growing seasons in 2002 and 2003

Year	Ecosystems	Daily ET flux (mean ± 1 S.D.) (mm day ⁻¹) and min–max	Periodic total ET/P	N (days)	Significance ^a
2002 (May–October) (P = 560 mm)	MHW	1.6 ± 1.3 (0.0–5.1)	0.52	171	A
	MRP	1.9 ± 1.2 (0.0–4.8)	0.61	163	A
	YHW	1.6 ± 0.9 (0.3–3.6)	0.51	169	A
	YRP	1.7 ± 0.1 (0.0–4.9)	0.55	179	A
	PB1	1.7 ± 1.1 (0.2–4.2)	0.50	178	A
2003 (May–October) (P = 608 mm)	MHW	2.0 ± 1.3 (0.0–5.8)	0.61	114	B
	MRP	1.9 ± 1.1 (0.1–4.7)	0.49	121	B
	IHW	1.8 ± 1.5 (0.0–6.1)	0.57	107	B
	IRP	2.0 ± 1.2 (0.0–5.5)	0.53	110	B
	PB2	1.4 ± 1.0 (0.0–4.2)	0.41	145	C
2002 (June–July) (P = 197 mm)	MHW	2.4 ± 1.1 (0.6–5.1)	0.75	61	D
	MRP	2.2 ± 1.2 (0.3–4.8)	0.68	61	D
	YHW	2.0 ± 0.9 (0.5–3.6)	0.62	61	D
	YRP	2.2 ± 0.9 (0.6–4.6)	0.69	61	D
	PB1	2.1 ± 1.0 (0.2–4.2)	0.65	61	D
2003 (June–July) (P = 201 mm)	MHW	2.7 ± 1.2 (0.6–5.8)	0.81	58	E
	MRP	2.6 ± 0.5 (0.1–4.7)	0.78	61	E
	IHW	3.0 ± 1.6 (0.6–6.1)	0.90	57	E
	IRP	2.7 ± 1.1 (0.4–5.5)	0.82	61	E
	PB2	2.1 ± 0.9 (0.9–4.2)	0.64	61	F

^a Different letter in the same group indicates significant difference at the 0.05 level by ANOVA. Significance tests were performed for the first two groups in column 1 with data for the period from June through September only.

season-to-season variation was more pronounced in these stands than others.

Modeled daily ET followed the seasonal patterns and measured ET trend well, especially during the peak ET periods in July for all sites (Fig. 6). However, the model overestimated ET noticeably for MHW, PB1, and PB2 during the spring (May–June) in both 2002 and 2003, and in August 2003 for the MRP and PB2 (Fig. 6). For both MRP and MHW, the model overestimated the measured ET on the monthly average basis. However, simulated monthly average ET corresponded more closely to ET measured for PB1 in 2002 and PB2 in 2003 than to measured ET for the mature forests (Fig. 7).

By the model assumption, when soil moisture is below field capacity, water stress would occur, and modeled actual ET would be less than PET. Our modeling identified at least one period of low ET each year due to soil moisture stress at the study sites when actual ET was lower than PET, and several stress periods for the low leaf area case. However, the model missed one obvious stress period (August 2002) as indicated by the eddy covariance measurements in the mature forests. The model tracked ET relatively better at the less-vegetated site (PB1 and PB2) where ET was mostly controlled by soil moisture through soil evaporation, which dominated the ET processes for those two sites. Therefore, we suggest that vapor pressure deficit (VPD) might have contributed to low ET during the observed dry periods for forested conditions with high leaf area index values (Fig. 6a).

The MIKE SHE model provided a complete year-round ET data set representing three types of managed stands: mature hardwoods, mature red pine, and a low-LAI stand representing the pine barren ecosystems (Fig. 8). Monthly ET was the highest during the summer months (June–August) (Fig. 8). Water deficits occurred in July as a result of high PET demand.

Water recharged the soil mostly during the fall months (September–October) when precipitation exceeded ET. Annual total ET for 2003 was similar to that for 2002, but predicted ET for August 2003 was 9–10 mm higher than that for August 2002, for reasons we have already discussed. Although July PET was higher in 2002 than in 2003, simulated ET for July 2002 was close to that for July 2003 due to soil moisture stress to tree transpiration in July 2002. Average annual ET for the mature red pine ecosystem was highest (ranging 575–596 mm/year or 80–86% of precipitation), followed by that for mature hardwoods (552–554 mm/year or 76–80% of precipitation) and that for the clearcut or pine barren system (462–466 mm/year or 64–67% of precipitation).

4. Discussion

The forest hydrology of Northern Wisconsin is largely controlled by the regional climatic characteristics and dynamics of water and energy inputs during the growing season from May to October. Forest management practices or other land disturbances (e.g., fire and diseases) associated with climate changes that alter water loss through the evapotranspiration process are likely to have profound impact on the water and energy balances in the region. Knowledge of the effects of management practices on energy and water flows in dominant ecosystems in the Upper Great Lakes region is very limited. This study contrasts total ET in selected individual ecosystems with contrasting tree species and tree age classes.

Daily ET varied greatly over the seasons, with rapid increase in May, peak in July, and decrease by the end of October. Simulation runs with MIKE SHE suggest that ET was

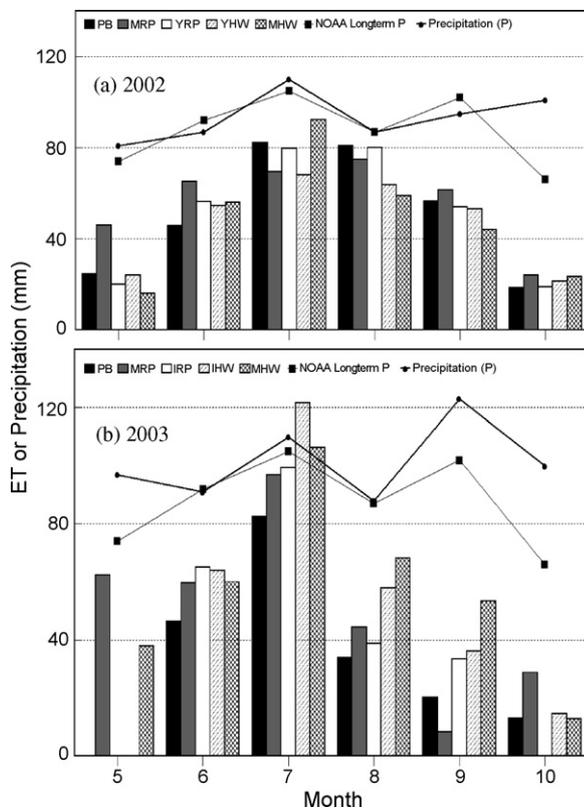


Fig. 5 – Comparison of monthly ET measured by the eddy covariance method for: (a) mature hardwood (MHW), mature red pine (MRP), recently clearcut hardwoods (YHW), young red pine (YRP), and pine barrens (PB1) during 2002; (b) mature hardwood (MHW), mature red pine (MRP), intermediate red pine (IRP), intermediate hardwoods (YHW), and burned pine barrens (PB2) during 2003.

limited by soil moisture availability in the summer. However, except in the PB1 and PB2 ecosystems, direct flux measurements did not show ET reduction. These discrepancies suggested that the hydrology-based model did not reflect the physiological control on mature tree transpiration. Recent studies using the sapflow and eddy flux methods at individual tree and ecosystem scale have shown clearly that VPD was the key environmental variable controlling forest transpiration through stomatal conductance in the Northern Wisconsin region (Ewers et al., 2002; Mackay et al., 2002). The MIKE SHE hydrologic model is based on physical environmental processes and does not account for physiological effects, including the potential effect of VPD on transpiration, and this may have compromised model predictions. Ecosystem modeling indeed suggests that soil moisture and VPD are important in carbon cycling, and thus ET at the study sites in general (Ryu et al., this issue).

Seasonal ET changes observed during this study followed closely the long-term seasonal distribution of precipitation in the region. On average, over 70% of annual precipitation in the region falls during the May–October growing season, and this ratio was as high as 78 and 85% in 2002 and 2003, respectively. The timing of water input (precipitation) and output (ET)

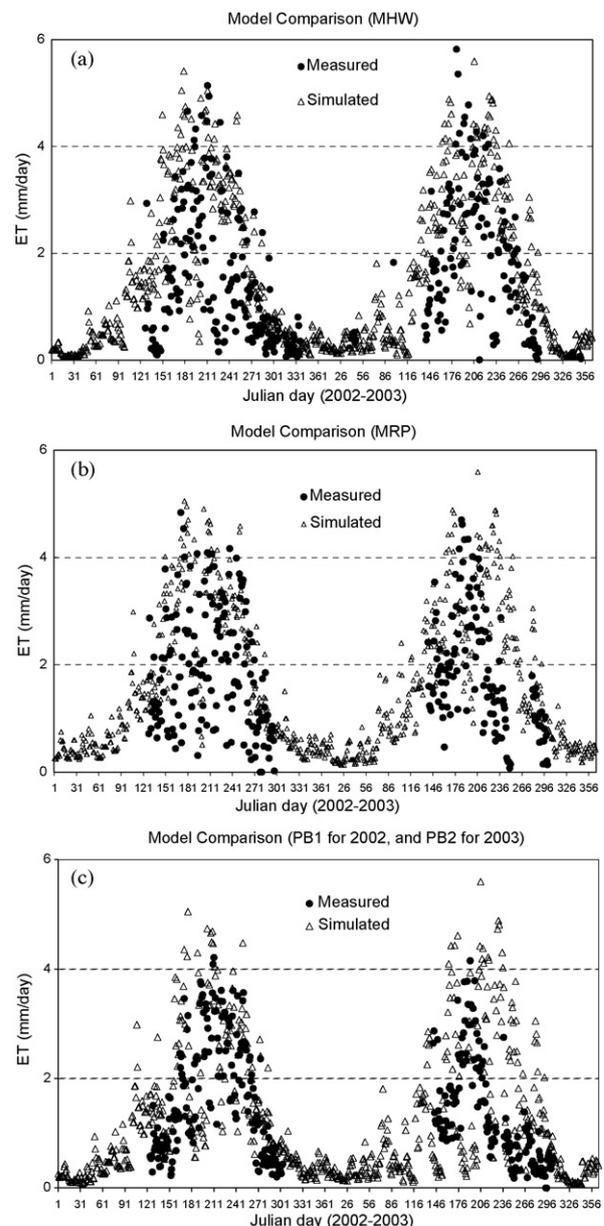


Fig. 6 – Comparison between simulated and measured daily ET for: (a) MRP ecosystem, (b) MHW ecosystem, and (c) PB1 and PB2 ecosystems during 2002–2003.

strongly influence ecosystem productivity, water availability, and water yield in the region. Any changes in the precipitation regime due to climatic variability and any changes in the ET fluxes due to land management will have more pronounced effects on water availability, ecosystem productivity, and water yield here than in regions such as the Eastern USA, where precipitation is distributed more uniformly throughout the year (Sun et al., 2004).

The amount of ET loss from one type of forest is largely controlled by leaf area (Gholz and Clark, 2002; Chen et al., 2004). Our field data and simulations also confirmed that mature forests with higher leaf area had higher ET in the growing season than those with lower leaf area, such as clearcut ecosystems and pine barrens. However, care must be

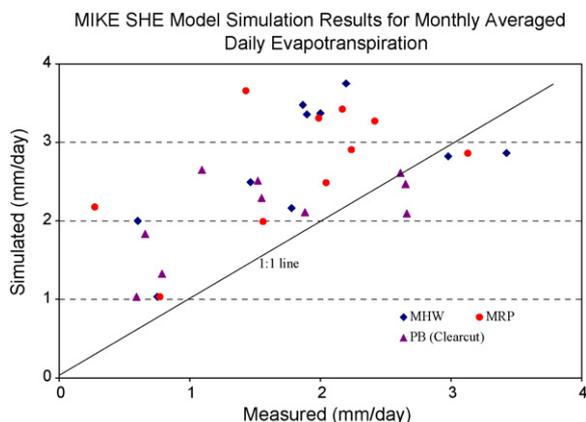


Fig. 7 – Comparison of computer simulated and field measured monthly averaged ET of MRP, MHW, and PB1 (2002) and PB2 (2003) (represented as clearcut). A general 21% over-prediction of the simulation model is shown.

taken when predicting ET at the landscape using leaf area as one indicator. Less known are the changes of each of the ET components (transpiration, canopy interception, and soil evaporation) during forest regeneration. Our data also indicated that LAI alone could not explain ET differences among different ecosystems with contrasting plant community types. For example, the pine barrens had low LAI but had ET characteristics similar to those of the mature forests (Figs. 4a and 5a). Our field data suggested that there were no significant differences between ET values for the hardwood and the coniferous forest during the growing seasons. However, the model simulations suggested that ET of the red pine forest was 6% higher than that of the hardwoods, presumably because the former had higher canopy interception and transpiration during the non-growing seasons when deciduous trees drop their leaves (Swank and Douglass, 1974). It appeared that both conifers and deciduous forests had recovered their ET capacity at age 8–25 years (Figs. 4b and 5b). This is consistent with findings of Noormets et al. (2007), who reported that stands became carbon sinks by age 10 suggesting

recovery of forest transpiration capacity. Also our finding are in good agreement with Verry (1986) who suggests that it takes 12–15 years for harvested aspen stands to recover their water yield during regeneration in the Lake States. In Minnesota, clearcutting of aspen and pine forests increased annual streamflow by 90 and 160 mm/year, respectively, resulting in a 30–80% increase in streamflow or recharge to groundwater (Verry, 1986). However, no detailed specific stand-level data were available to validate these differential responses (Verry, 1986). Our June and July data showed that mature forests lost 5–21% more water (≈ 30 mm) in 2002 and 22–42% more water (28–64 mm) in 2003 than ecosystems with low LAI (e.g., PB1, PB2, or YHW). These data provide direct evidence that mature forests use more water than other forest stands during peak seasons. In addition, our simulations indicated that converting mature hardwoods or mature red pine to young regenerating stands would reduce annual ET by 90 and 121 mm, respectively—a range close to values reported by Verry (1986). This water loss is significant in terms of local streamflow and water supply, although the amount of water lost is much smaller than the hydrologic response to forest removal in the Eastern USA, which is often 200–400 cm/year (Ice and Stednick, 2004).

We found noticeable differences between modeled daily ET as predicted by the hydrologic model, and measured daily ET as determined by the eddy covariance method. Estimation errors were expected for both methods. The eddy covariance method does not provide tight energy closure consistently, and energy closure is very relevant to evaluation of latent heat flux (Wilson et al., 2002) and thus estimation of ET and water balance. Wilson et al. (2002) reported an average energy imbalance of 20% when comparing the sum of LE and sensible heat with available energy (net radiation less energy stored) in a recent review of 22 sites and 50-site years in FLUXNET, a network of eddy covariance sites. We expected to find measurement errors of similar magnitude in our study. Error in model prediction may result from inaccuracy of model parameterization of soils and groundwater systems and from inaccuracy in simulating the physiological controls (e.g., the effect of VPD on transpiration processes).

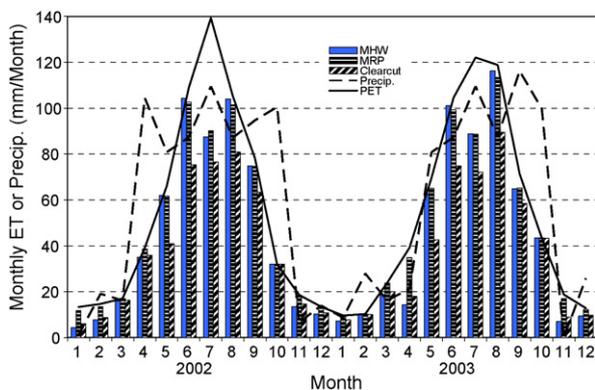


Fig. 8 – Simulated monthly ET (mm) distributions during 2002–2003 in three contrasting ecosystems, mature red pine (MRP), mature hardwood (MHW), and clearcut representing pine barrens.

5. Conclusion

This study compared ET estimates based on field eddy covariance measurements over two growing seasons (May–October) with computer simulation modeling results in eight dominant ecosystems in a managed landscape in Northern Wisconsin. Comparisons of field data and modeling results were useful in quantifying ET flux at multiple temporal scales, especially as the accuracy of field sampling techniques and models in landscape-scale studies is still limited. We conclude that: (1) prescribed burning that dramatically reduces leaf area reduced ET significantly in the growing seasons; (2) leaf area is not a good indicator of landscape-scale ET; (3) ecosystem ET of regenerated forests recovers from the effects of harvesting by forest age 8–25 years; (4) overall, simulated ET was higher than values obtained by the eddy covariance method. The hydrological model, MIKE SHE, was mostly based on the physical processes of water cycles of a forest stand. Although it is still

useful for identifying the general trend of ET, it lacks consideration of the effects of VPD and stomatal activity on tree transpiration. This shortcoming might have caused the ET overestimation when comparing to the eddy covariance method. Future ecosystem-scale independent water balance studies are needed to fully quantify the ET differences among the major ecosystems in Northern Wisconsin.

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