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Impacts of precipitation seasonality and ecosystem types on evapotranspiration in the Yukon River Basin, Alaska

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[1] Evapotranspiration (ET) is the largest component of water loss from terrestrial ecosystems; however, large uncertainties exist when estimating the temporal and spatial variations of ET because of concurrent shifts in the magnitude and seasonal distribution of precipitation as well as differences in the response of ecosystem ET to environmental variabilities. In this study, we examined the impacts of precipitation seasonality and ecosystem types on ET quantified by eddy covariance towers from 2002 to 2004 in three ecosystems (grassland, deciduous broadleaf forest, and evergreen needleleaf forest) in the Yukon River Basin, Alaska. The annual precipitation changed greatly in both magnitude and seasonal distribution through the three investigated years. Observations and model results showed that ET was more sensitive to precipitation scarcity in the early growing season than in the late growing season, which was the direct result of different responses of ET components to precipitation in different seasons. The results demonstrated the importance of seasonal variations of precipitation in regulating annual ET and overshadowing the function of annual precipitation. Comparison of ET among ecosystems over the growing season indicated that ET was largest in deciduous broadleaf, intermediate in evergreen needleleaf, and lowest in the grassland ecosystem. These ecosystem differences in ET were related to differences in successional stages and physiological responses.

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1. Introduction

[2] Evapotranspiration (ET) plays an important role in governing the soil moisture, vegetation productivity, carbon cycle, and water budget in terrestrial ecosystems [Dirmeyer, 1994; Betts and Ball, 1997; Pielke *et al.*, 1998]. ET is difficult to measure and predict, however, especially at large spatial scales [Turner, 1989]. Although a consensus has been reached about the increased precipitation and runoff under climate change [Dai *et al.*, 1997; Hulme *et al.*, 1998; Gedney *et al.*, 2006; International Panel on Climate Change (IPCC), 2007], the trend for ET is still being debated [Brutsaert and Parlange, 1998; Liepert *et al.*, 2004; Ryu *et al.*, 2008].

[3] This lack of consensus stems in part from the concurrent shifts in the magnitude of precipitation and its seasonal distribution [Dore, 2005]. It has long been recognized that available energy and precipitation are the primary factors that determine the annual rate of ET. On a mean annual basis, actual ET will approach annual precipitation in very dry climate zones; while under very wet conditions, actual ET asymptotically approaches the potential evapotranspiration [Priestley and Taylor, 1972; Zhang *et al.*, 2001]. On the basis of these considerations, a number of empirical relationships have been developed for quantifying mean annual ET [Pike, 1964; Budyko, 1974]. However, other studies suggested that precipitation influences ecosystems in nonlinear fashions [Fang *et al.*, 2005], and there can be large differences regarding the relationship between annual precipitation and ET due to the profound effects of precipitation seasonality [Milly, 1994; Zhang *et al.*, 2001, 2004]. Estimates of mean annual evapotranspiration from the dynamic global vegetation model compared poorly with observational data, because the exclusion of precipitation seasonal variation was not sufficient to explain variability in the mean annual water balance [Potter *et al.*, 2005]. Recent model analyses also supported the conclusion that changes in precipitation seasonality have profound impacts on transpiration across five major terrestrial ecosystems [Luo *et al.*, 2008; Gerten *et al.*, 2008].

[4] Physiological and phenological differences among ecosystem types are likely to modulate the response of

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Table 1. Name, Location, and Other Characteristics of the Three Study Sites

Site	Burn1999	Burn1987	Control
Location	63°55'N, 145°44'W	63°55'N, 145°23'W	63°53'N, 145°44'W
Ecosystem type	grassland	deciduous broadleaf forest	evergreen needleleaf forest
Stand age ^a (years)	4	16	~80
Disturbances	crown fire occurred in 1999	crown fire occurred in 1987	fire occurred around 1920
Soil organic matter (kg m ⁻²)	2.89	–	4.17
Soil depth (m)	0.47	–	0.15
Dominant species	bunch grasses (<i>Festuca altaica</i>) and deciduous shrubs	aspen and willow (<i>Populus tremuloides</i> and <i>Salix</i> spp.)	black spruce (<i>Picea mariana</i>)

^aTo 2002, which is the first eddy covariance observation year.

ecosystem ET to climate variability [Falge *et al.*, 2002]. Regional studies, for example, have reported more than twofold differences in ET among the various forest types of northern Wisconsin, primarily because of differences in tree hydraulic conductance [Sun *et al.*, 2008]. Attributes concerning the absorption of solar radiation and the exchange of mass and energy with the atmosphere also vary greatly among ecosystems; this is attributed to different community structures, which directly affect ecosystem ET [Baldocchi *et al.*, 2000; Liu and Randerson, 2008].

[5] The high-latitude region is of particular interest and importance to global change studies because it experiences distinct climate change and disturbances [Wein and MacLean, 1983; IPCC, 2007]. A number of studies have shown that middle- and high-latitude regions experience an increased precipitation of between 7% and 12%, which is much higher than the global average increase of 2% [Jones and Hulme, 1996; Hulme *et al.*, 1998; IPCC, 2007]. More importantly, increased precipitation mostly occurred in autumn and winter [IPCC, 2007], resulting in the significant changes in precipitation seasonal distribution. Furthermore, in the past decades, ecosystem types have been altered greatly by disturbances caused by increasing fire related to climate warming in northern regions [Goetz *et al.*, 2007]. The frequency of fires is also projected to increase in the future [Flannigan *et al.*, 2005]. The probability of fire in old evergreen conifer stands is much higher than in deciduous stands [French *et al.*, 1996]; and more fire increases the relative abundance of early successional to midsuccessional deciduous stands compared to older evergreen conifer stands [Chapin *et al.*, 2000; Chambers and Chapin, 2002], thus leading to changes in radiative exchange and the surface energy budget at the regional scale. To our knowledge, the impacts of precipitation seasonality and ecosystem types on ET have not been extensively investigated because of data limitation in high-latitude regions.

[6] Here, we report measurements of ET from eddy covariance towers over 3 years (2002–2004) in interior Alaska at three adjacent ecosystems: deciduous broadleaf forest, evergreen needleleaf forest, and grassland. Distinct differences in the seasonal distribution of precipitation were observed, offering an opportunity to investigate the effects of precipitation seasonality on ET and compare the relative effects of the same climate variability on ET in different ecosystem types. Moreover, an ecosystem model (Integrated Biosphere Simulator (IBIS)) [Foley *et al.*, 1996] was used to study the responses of ET components (i.e., intercepted water evaporation by vegetation canopy, vegetation transpiration, and soil evaporation) to precipitation seasonality in order to examine regulating mechanisms of precipitation

seasonality to ET. Our objectives were (1) to investigate the effects of precipitation seasonality and ecosystem types on ET, (2) to examine responses of ET components to precipitation seasonality, and (3) to analyze the effects of precipitation seasonality on the coupling of gross primary production (GPP) and ET (indicated by water use efficiency, WUE).

2. Materials and Methods

2.1. Site Description

[7] Three adjacent eddy covariance towers locate near Delta Junction (63°54'N, 145°40'W) in interior Alaska. The study sites experience a continental climate with large daily and annual temperature ranges, low humidity, and relatively low precipitation. The annual average temperature and annual precipitation are –2.1°C and 289.8 mm, respectively (1937–2005 data from the Western Regional Climate Center (WRCC), station observations available from Big Delta, Alaska). The soil consists of well-drained silty loams on top of glacial moraines [Manies *et al.*, 2004; Liu and Randerson, 2008]. Specific site information was summarized in Table 1.

2.2. Eddy Flux Measurements and Data Processing

[8] Turbulent fluxes of sensible heat, latent heat, and CO₂ were measured using an eddy covariance system on a micrometeorological tower at each site from 1 January 2002 to 29 September 2004 (since April 2002 for the grassland site). Details of the flux measurements and data acquisitions were introduced by Liu *et al.* [2005], Welp *et al.* [2007], and Liu and Randerson [2008].

[9] An outlier (“spike”) detection technique was applied, and the spikes were removed, following Papale *et al.* [2006]. Because nighttime CO₂ flux can be underestimated by eddy covariance measurements under stable conditions [Falge *et al.*, 2001], nighttime data with nonturbulent conditions were removed on the basis of a friction velocity threshold criterion (site-specific 99% threshold criterion following Reichstein *et al.* [2005] and Papale *et al.* [2006]).

[10] Although the intent is to obtain continuous flux and meteorological variables measurements, data gaps are unavoidable because of system failure or data rejection. For latent heat (LE, equivalent to ET), we filled short data gaps (<3 h) with linear interpolation, and we used the mean diurnal method for filling longer gaps [Falge *et al.*, 2001]. The diurnal means were calculated for 26 consecutive day windows, which correspond well with a spectral gap in energy fluxes at the site [Baldocchi *et al.*, 2004].

[11] For assessing the data quality, *Liu and Randerson* [2008] analyzed the linear regressions of the sum of LE and sensible heat (H) against the difference between net radiation (R_n) and soil heat flux (G). The half-hourly data, which excluded gap-filled data, were used to perform the linear regression analysis. During 2002–2004, annual mean values of the slopes and intercepts of $H + LE$ versus $R_n - G$ are 0.79 and 6.93 for the grassland site, 0.84 and 3.8 for the deciduous broadleaf forest site, and 0.86 and 7.4 for the evergreen needleleaf forest site [*Liu and Randerson*, 2008]. These closure estimates are within the range of those reported by the FLUXNET community [*Wilson et al.*, 2002].

[12] Nonlinear regression methods were used for filling eddy covariance flux of CO_2 (F_c) data gaps [*Falge et al.*, 2001] in order to estimate GPP [*Yuan et al.*, 2007; *Desai et al.*, 2008]. The nonlinear regression procedure (Proc NLIN) in the Statistical Analysis System (SAS) (SAS Institute Inc., Cary, North Carolina, USA) was applied to fit the relationships between measured fluxes and controlling environmental factors using a 15 day moving window. The Van't Hoff [" Q_{10} "; see *Lloyd and Taylor*, 1994] equation was used to fill the missing nighttime CO_2 fluxes ($F_{c,\text{night}}$):

$$F_{c,\text{night}} = Ae^{(BT_a)}, \quad (1)$$

where A and B are fit model parameters. A Michaelis-Menten light response equation was used to fill the missing daytime fluxes ($F_{c,\text{day}}$) [*Falge et al.*, 2001]:

$$F_{c,\text{day}} = \frac{\alpha \times \text{PAR} \times F_{\text{GPP,sat}}}{F_{\text{GPP,sat}} + \alpha \times \text{PAR}} - F_{\text{RE,day}}, \quad (2)$$

where $F_{\text{GPP,sat}}$ (GPP at saturating light) and α (initial slope of the light response function) are fit parameters, and $F_{\text{RE,day}}$ (ecosystem respiration during the day) was estimated by extrapolation of equation (1) using the daytime air temperature.

[13] For periods with missing solar radiation, air temperature, and precipitation data, we used the measurements from the other two companion sites. We compared numerous meteorological variables between the three sites and found that they were interchangeable [*Liu et al.*, 2005].

[14] Monthly net ecosystem exchange (NEE), ecosystem respiration (Re), LE, meteorological variables, and soil moisture were synthesized on the basis of half-hourly values. GPP was calculated as the sum of NEE and Re.

2.3. Satellite Data

[15] MODIS data used in this study are MODIS ASCII subset data generated with Collection 5 algorithms and were downloaded directly from the MODIS land product subsets website (<http://www.modis.ornl.gov>). MODIS LAI 8 day composites at 1 km spatial resolution were used in this study. Only the LAI values of the pixel containing the tower were used. Quality control (QC) flags, which indicate cloud contamination in each pixel, were examined to screen and reject LAI data of insufficient quality.

2.4. Ecosystem Model and Simulations

[16] Version 2.6 of IBIS [*Kucharik et al.*, 2000] was used in this study. This model is hierarchically organized to allow for explicit coupling among ecological biophysical and

physiological processes at different timescales [*Foley et al.*, 1996]. The model simulates the energy, water, carbon, and momentum balance of the soil-plant-atmosphere system at a half-hourly time step using the land surface scheme (LSX) of *Pollard and Thompson* [1995]. The total amount of evapotranspiration from the land surface is treated as the sum of three water vapor fluxes: evaporation from the soil, evaporation of water intercepted by vegetation canopies, and canopy transpiration. Rates of transpiration depend on canopy conductance and are calculated independently for each plant type within the canopy. To account for evaporation from intercepted rain, the model describes the interception and cascade of precipitation (both rain and snow) through the canopies.

[17] IBIS uses a multilayer formulation of soil to simulate the diurnal and seasonal variations of heat and moisture in the soil. The eight soil layers in IBIS have top-to-bottom thicknesses of 0.10, 0.15, 0.25, 0.50, 1.0, 2.0, and 4.0 m. At any time step, each layer is described in terms of soil temperature, volumetric water content, and ice content [*Pollard and Thompson*, 1995; *Foley et al.*, 1996]. The IBIS soil physics module uses Richard's equation to calculate the rate of change of liquid soil moisture and Darcy's law to model the vertical flux of water [*Campbell and Norman*, 1998]. The water budget of soil is controlled by the rate of infiltration evaporation of water from the soil surface, the transpiration stream originating from plants, and redistribution of water in the profile.

[18] Physiologically based formulations of leaf-level photosynthesis [*Farquhar et al.*, 1980], stomatal conductance [*Ball et al.*, 1986; *Collatz et al.*, 1991, 1992], and respiration [*Ryan et al.*, 1995] control the canopy exchange processes. Leaf-level photosynthesis is scaled to the canopy level by assuming that photosynthesis is proportional to the absorbed photosynthetically active radiation (APAR) within the canopy.

[19] Daily micrometeorological observations from three eddy covariance sites were used to drive IBIS simulations. These observations included average air temperature, minimum air temperature, maximum air temperature, precipitation, net radiation, wind speed, and air pressure. We used satellite leaf area index (MODIS-LAI product) to replace the simulated LAI. MODIS LAI data were only available at an 8 day time step; thus, daily LAI values were derived from two consecutive 8 day composites by linear interpretation.

[20] The parameters optimization was accomplished using the software PEST [*Watermark Numerical Computing*, 2003]. PEST takes control of the IBIS model and runs it as many times as necessary to reach an optimal set of parameter values. PEST calculates the mismatch between the model output and the observation data, and then determines the best way, by adjusting the values of model parameters, to correct the mismatch. This process is repeated until the mismatch is minimized. The corresponding final set of parameter values are said to be optimal. In this study, we optimized several model parameters for each site, and minimize the joint mismatch of ecosystem GPP, ET, and soil moisture content. Seven parameters were selected to optimize, which are related to simulations of GPP, ET, and soil moisture content (Table 2). Maximum Rubisco capacity at 15°C of the top leaf and intrinsic quantum efficiency are major physiological parameters for regulating vegetation production. Slope and

Table 2. Vegetation and Soil Parameters for Model Simulations

Model Parameters	Deciduous Broadleaf Forest	Grassland	Evergreen Needleleaf Forest
Maximum Rubisco capacity at 15°C of the top leaf ($\mu\text{mol m}^{-2} \text{s}^{-1}$)	30	18	25
Intrinsic quantum efficiency	0.06	0.03	0.04
Slope of the conductance-photosynthesis relationship	7.23	8.01	3.59
Intercept of the conductance-photosynthesis relationship	0.21	0.56	0.34
Saturated hydraulic conductivity (m/d)	0.25	0.48	0.89
Saturated air entry potential (m)	0.15	0.31	0.51
Soil b parameter	4.21	3.81	2.80

intercept of the conductance-photosynthesis relationship directly determine the connection of vegetation and transpiration. The other three parameters (i.e., saturated hydraulic conductivity, saturated air entry potential, and soil b parameter) are critical for predicting soil moisture content.

[21] We used model simulation to separate ET components (i.e., vegetation transpiration, soil surface evaporation, and vegetation canopy interception evaporation) under realized climatic conditions at three ecosystems in order to investigate their seasonality and responses to precipitation seasonality. In addition, we conducted a model experiment under control climatic scenario by using mean air temperature of 2002 and 2003 to replace that of 2004, and compared variations of GPP and ET at realized and control climatic scenarios, in order to separate the influences of warming and precipitation seasonality (see section 3.4). Another model experiment was conducted to examine impacts of precipitation in the previous year on the response of ET to precipitation seasonality. In this model experiment, precipitation pattern of 2002 was replaced by that of 2004, which made a precipitation scenario of a spring drought in 2003 following an autumn drought, and the simulations were compared to that under the realized precipitation condition.

3. Results

3.1. Interannual Variability of Environmental Variables

[22] The interannual variability of air temperature was pronounced in the study area, and air temperature over the growing season was remarkably higher in 2004 than other years (Figure 1a). The long-term average air temperature from April to September was 9.5°C (Western Regional Climate Center, 2006, <http://wrcc.dri.edu>). The years 2002 and 2003 were comparatively cool (9°C and 9.1°C), and 2004 was comparatively warm (11.2°C).

[23] The total amount of precipitation and seasonal distribution varied widely from year to year (Figure 1b). The annual precipitation was 300 mm in 2002, which was slightly higher than the long-term average of 289.8 mm in the study area during 1937–2005 (station observations in Big Delta), whereas precipitation in 2003 (190 mm) and 2004 (149 mm) were below average. Moreover, there were significant differences in seasonal distribution of precipitation at the study area. In the first year (2002), precipitation distribution followed the long-term average distribution over the growing season (from May to September). However, only 9.37 mm of precipitation was received in May and June of 2003, which was 12% of the long-term average (1937–2005) at the corresponding period (Figure 1b). In contrast, 18 mm

of precipitation occurred in July and August of 2004 (Figure 1b), equivalent to 16% of the long-term average.

[24] The vapor pressure deficit (VPD) was strongly seasonal, with peaks in June (Figure 1c). The combined effects of air temperature and precipitation led to interannual variability of VPD. VPD was highest in the warmest year (2004) through the most months and stayed high during the late growing season of 2004 because of precipitation scarcity.

[25] Soil water content (SWC) appeared highly variable from month to month and followed the patterns of precipitation among different years (Figure 1d). SWC approached saturation in spring due to snowmelt and began to decrease in June until precipitation recharged soil water. Scarce precipitation in spring 2003 caused distinct decreases of SWC compared to the other 2 years from April to June. In addition, the study area experienced severe drought in July and August 2004 with total precipitation less than 20 mm, leading to extremely low SWC.

3.2. Comparisons of ET Among the Ecosystems

[26] ET demonstrated strong seasonality (Figure 2). It was small ($<0.2 \text{ mm d}^{-1}$) in winter while ecosystems were snow covered, increased substantially immediately after snowmelt in early April, then reached its peak in June and July. After July, ET started to decline, driven by decreases of available energy and plant senescence.

[27] Monthly mean ET in different phenophases varied greatly among the three ecosystems. At the beginning of the growing season, significantly higher ET was observed in evergreen needleleaf forest compared to the other two ecosystems (Figure 2). However, during the medium term of growing season (June–August), ET was the largest in deciduous broadleaf forest, intermediate in evergreen needleleaf forest, and the lowest ET in grassland (Figure 2). On average, daily ET was $1.73 \pm 0.53 \text{ mm}$ in deciduous broadleaf forest during June and August across the three study years, and was significantly higher than that of grassland ($1.19 \pm 0.27 \text{ mm}$) and evergreen needleleaf forest ($1.40 \pm 0.24 \text{ mm}$). At the annual scale, however, through the two entire years (2002 and 2003), there was higher magnitude of ET in deciduous broadleaf forest ($229 \pm 15 \text{ mm yr}^{-1}$) than evergreen needleleaf forest ($215 \pm 23 \text{ mm yr}^{-1}$), and grassland showed the lowest annual ET of $193 \pm 11 \text{ mm}$. Through the entire measurement periods, the ratios between cumulative ET and cumulative precipitation were 105%, 97%, and 85% in deciduous broadleaf forest, evergreen needleleaf forest, and grassland, respectively.

3.3. Ecosystem-Dependent Response of ET to Precipitation Seasonality

[28] ET at all sites was significantly reduced with shortage of precipitation in May and June 2003, leading to a

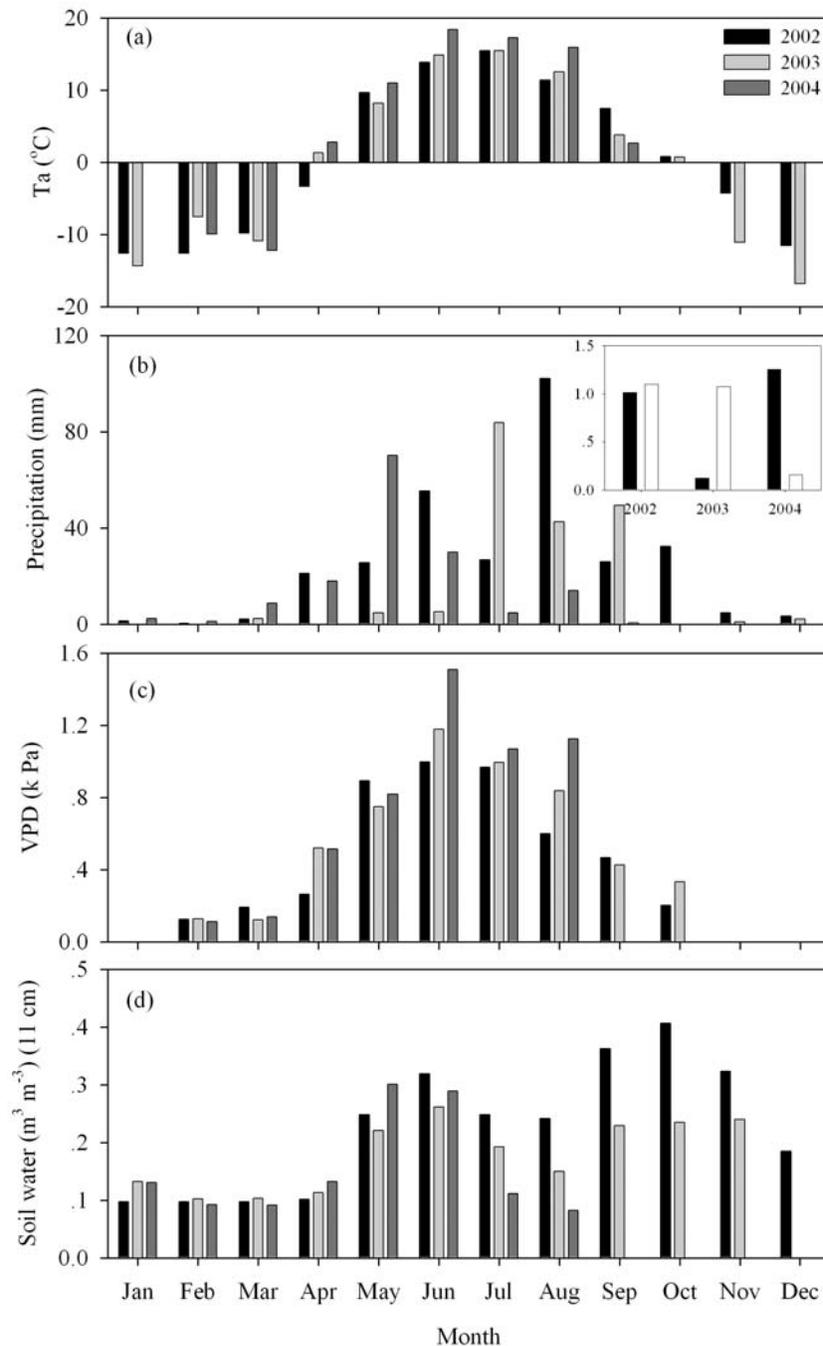


Figure 1. Monthly mean climate conditions in the study area (illustrated by the case of deciduous broadleaf forest site): (a) air temperature, (b) precipitation, (c) vapor pressure deficit (VPD), and (d) soil volumetric water content measured at 11 cm soil depth. The inset in Figure 1b indicates the ratio between precipitation from May to June (black bars) and July to August (white bars) with long-term averages of the corresponding period.

decrease in ET of 27%, 24%, and 24% (relative to the average values of the other 2 years) in deciduous broadleaf forest, evergreen needleleaf forest, and grassland, respectively (Figure 3). In contrast, precipitation scarcity in July and August only led to significant decreases of ET (35%) in the deciduous broadleaf forest (Figure 3a), but not in the grassland and the evergreen needleleaf forest (Figures 3b and 3c). Consequently, from January to August, ET was the largest in 2004 with the lowest precipitation because a

higher proportion of precipitation was allocated during the early growing season (Figure 4) and the lowest in 2003 with a moderate sum of precipitation due to precipitation scarcity at the corresponding period. In addition, the ratios between ET and potential ET were larger in 2002 and 2004 than that in 2003 due to the shortage of precipitation in the early growing season in 2003 (Table 3).

[29] IBIS successfully simulated ET, GPP, and soil moisture at the three ecosystems with the R^2 between measured

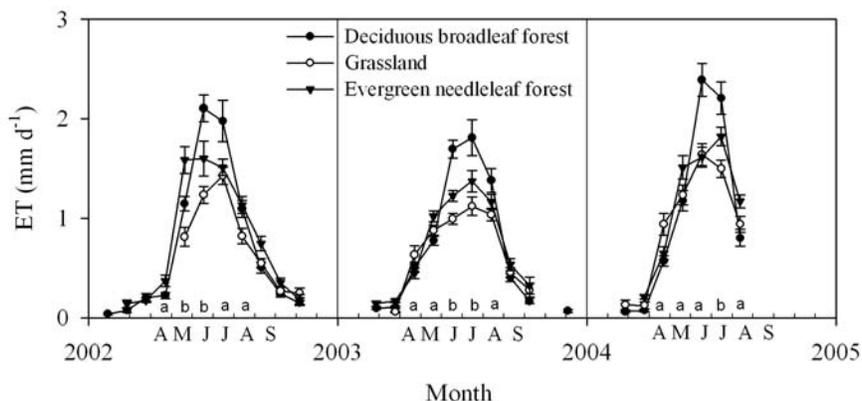


Figure 2. Seasonal dynamics of ET in three ecosystems. Analysis of variance ANOVA was used to test the differences among the different groups. Letter “a” indicates the significant differences of ET between two ecosystems, and “b” indicates significant differences of ET among all three ecosystems.

and modeled above 0.8 (Figure 5). The optimized parameters are showed in Table 2. The model obviously underestimated ET of 2004 for grassland and evergreen needleleaf forest by 11% and 18%, respectively. In contrast, the model

overestimated ET by 17% for deciduous broadleaf forest during the growing season through the entire study periods. The simulated GPP was in good agreement with the measurements for the relative predictive errors being 24%,

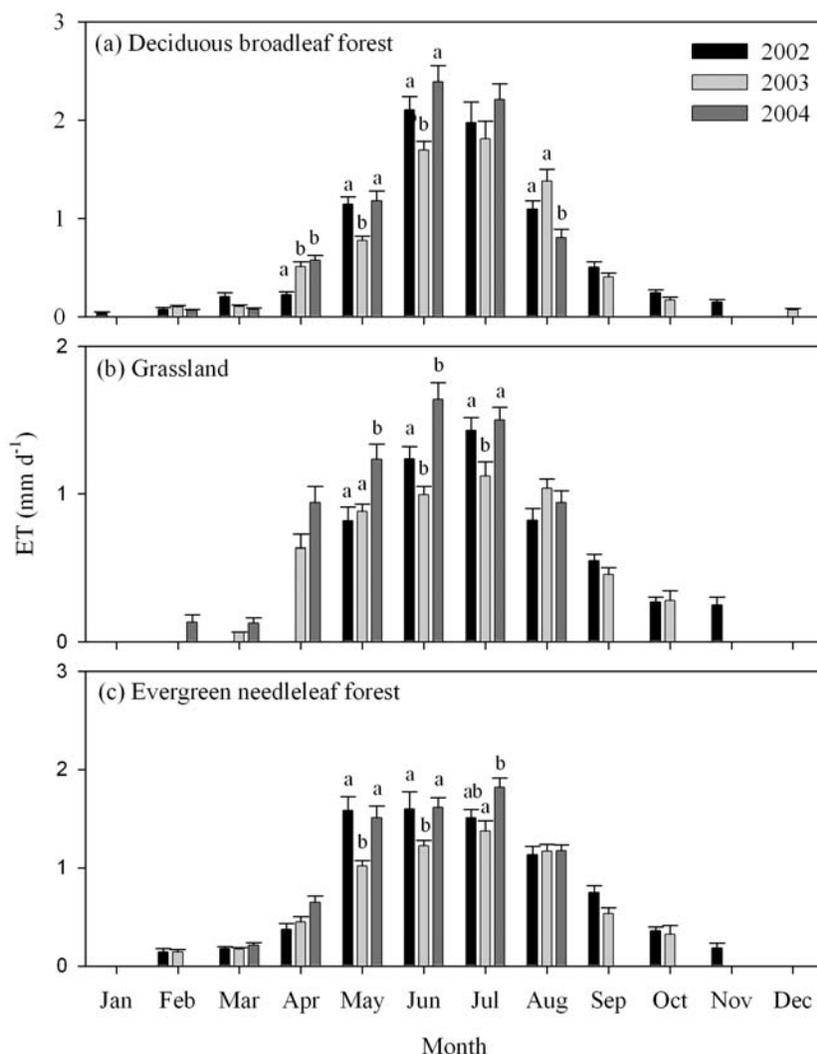


Figure 3. Monthly mean actual ET from 2002 to 2004 in the three study sites. Different letters indicate significant difference ($P < 0.05$) among the years.

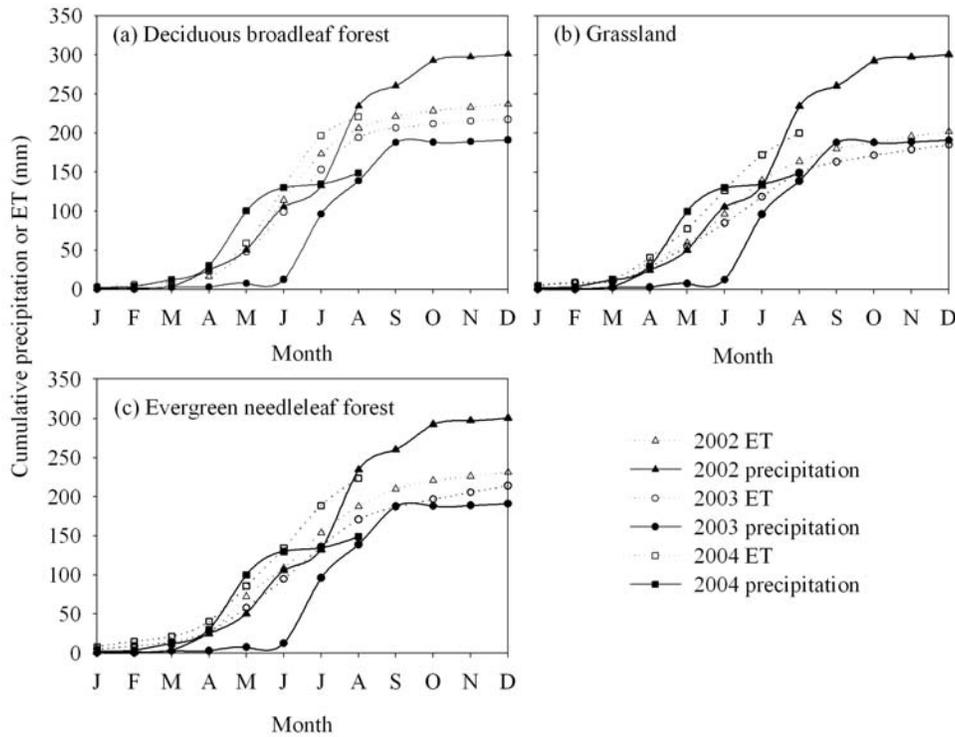


Figure 4. Annual cumulative precipitation and actual ET from 2002 to 2004 in the three study sites.

15%, and 15% for deciduous broadleaf forest, grassland, and evergreen needleleaf forest, respectively (Figures 5d–5f). The estimated soil moisture of the soil layer from the soil surface to 10 cm depth was generally in good agreement with the measurement at 11 cm depth through the 3 years at each site (Figures 5g–5i). The model slightly overestimated the soil moisture for 2002 at grassland sites and that of 2002 and 2003 for the evergreen needleleaf forest site during the growing season.

[30] At all three sites, evaporation of canopy-intercepted water was significantly reduced by a shortage of precipitation in May and June 2003 as well as in July and August 2004 (Figures 6a–6c). Precipitation scarcity in May and June of 2003 resulted in significant decreases of soil evaporation (E_S) by 27%, 16%, and 27% in 2002 for deciduous broadleaf forest, grassland, and evergreen needleleaf forest, respectively. The decreased magnitude of E_S was quite lower in July and August 2004 compared to 2002 with 17%, 5%, and 15% for deciduous broadleaf forest, grassland, and evergreen needleleaf forest, respectively. Precipitation scarcity neither in May and June 2003 nor in July and August 2004 leads to significant decreases of vegetation transpiration (E_V) at the three ecosystems.

[31] It was worth noting that there was significantly higher air temperature in 2004 compared to the other 2 years. It is indispensable to separate the influences of warming and precipitation seasonality to ET in 2004 by a model experiment. We made a control climatic scenario by replacing air temperature of 2004 with mean air temperatures of 2002 and 2003 and compare simulated ET between realized and control climatic conditions. The results showed ET slightly higher in warming conditions than control conditions, but the increases of ET were not significant during July and August at the three ecosystems (Figure 7). Specially, canopy-intercepted

evaporation did not show significant change under control conditions compared to warming conditions, and soil evaporation only significantly decreases during the early growing season. In contrast, decreased temperature in the control scenario significantly decreased vegetation transpiration at the three ecosystems compared with realized warming conditions.

3.4. Interannual Variability of Water Use Efficiency

[32] The relationship between monthly mean values of GPP and ET remained linear through the 3 years at all three sites (Figure 8). The slopes of the regression lines indicated that the averaged ecosystem WUE were quite different: 2.43, 1.69, and 1.03 $\text{g C mm}^{-1} \text{H}_2\text{O}$ for deciduous broadleaf forest, evergreen needleleaf forest, and grassland, respectively.

[33] In May and June, ecosystem WUE was significantly higher in 2003 and 2004 than 2002 (Figure 9) for both evergreen needleleaf forest and deciduous broadleaf forest. During the late growing season, WUE did not differ significantly among the 3 years at the three sites. For the deciduous broadleaf forest site, compared to that in August

Table 3. Annual Summary of the Ratio of Cumulative Actual ET with Potential ET

Year	Grassland	Deciduous Broadleaf Forest	Evergreen Needleleaf Forest
2002	0.70	0.67	0.52
2003	0.56	0.56	0.46
2004 ^a	0.64	0.63	0.51
Mean	0.63	0.62	0.49

^aIn 2004, observation periods were from January to August.

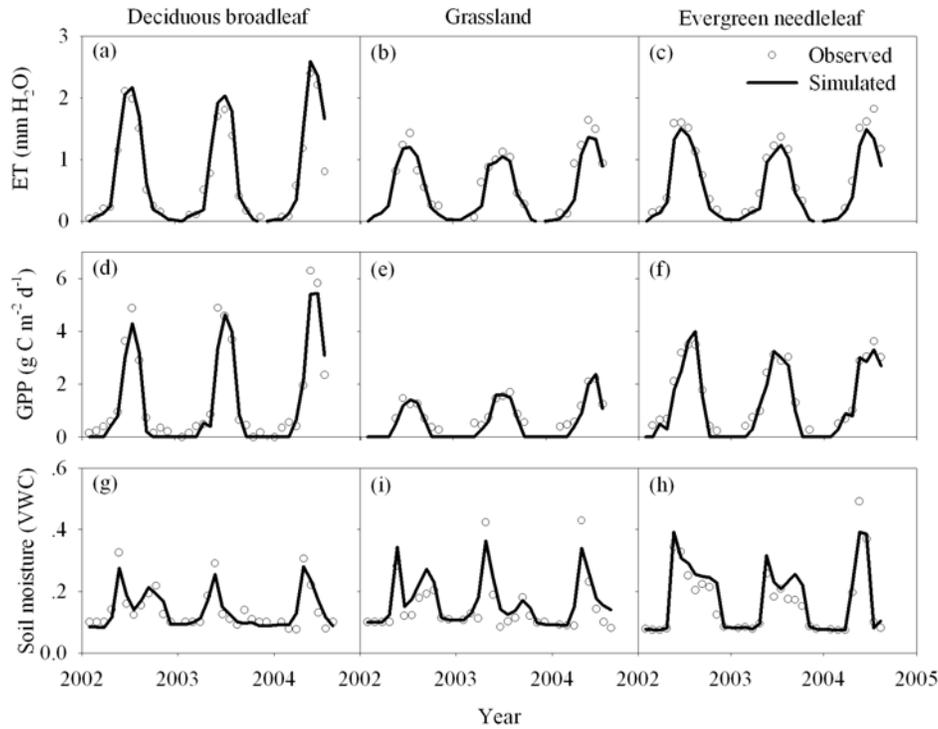


Figure 5. Model validation of (a–c) ET, (d–f) GPP, and (g–h) soil moisture at three ecosystems (deciduous broadleaf forest, Figures 5a, 5d, and 5g; grassland, Figures 5b, 5e, and 5h; evergreen needleleaf forest, Figures 5c, 5f, and 5j).

2002, WUE increased 12% in 2004 though the difference was not significant.

4. Discussions

4.1. Effects of Ecosystem Types on ET

[34] Annual ET was $229 \pm 15 \text{ mm yr}^{-1}$, $193 \pm 11 \text{ mm yr}^{-1}$, and $215 \pm 23 \text{ mm yr}^{-1}$ in deciduous broadleaf forest,

grassland, and evergreen needleleaf forest, respectively, during two entire study years (2002 and 2003), which were close to many published values of annual ET from the high-latitude ecosystems. They were comparable to recorded ET rates of 255 mm [Wever et al., 2002], 225 mm [Amiro et al., 2006], 237 mm [Kljun et al., 2006], and 218 mm [Nijssen et al., 1997] over a boreal grassland, a mixed forest, an

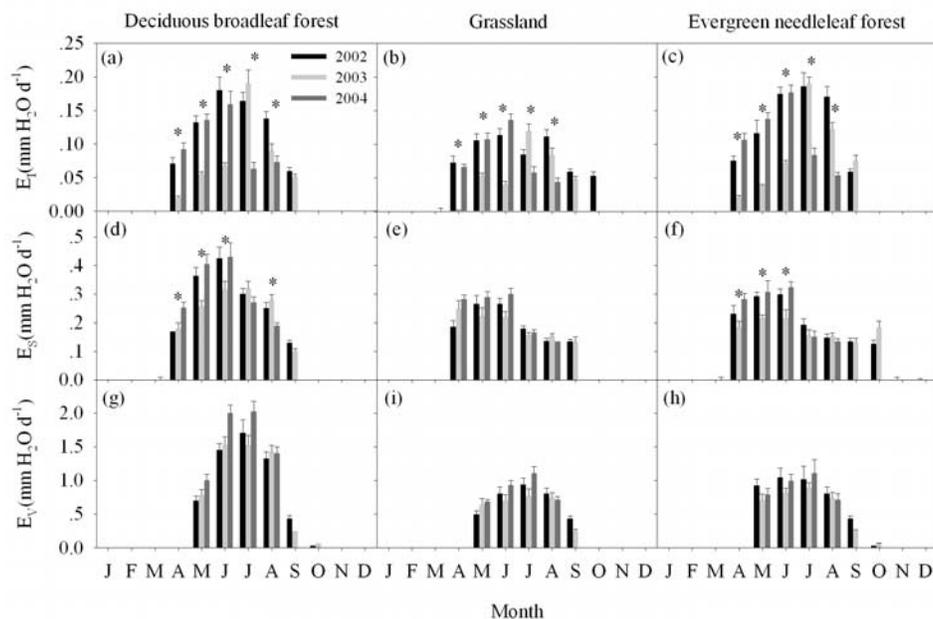


Figure 6. Monthly mean (a–c) canopy intercepted evaporation (E_t), (d–f) soil evaporation (E_s), and (g–i) vegetation transpiration (E_v) at three ecosystems through the entire study periods.

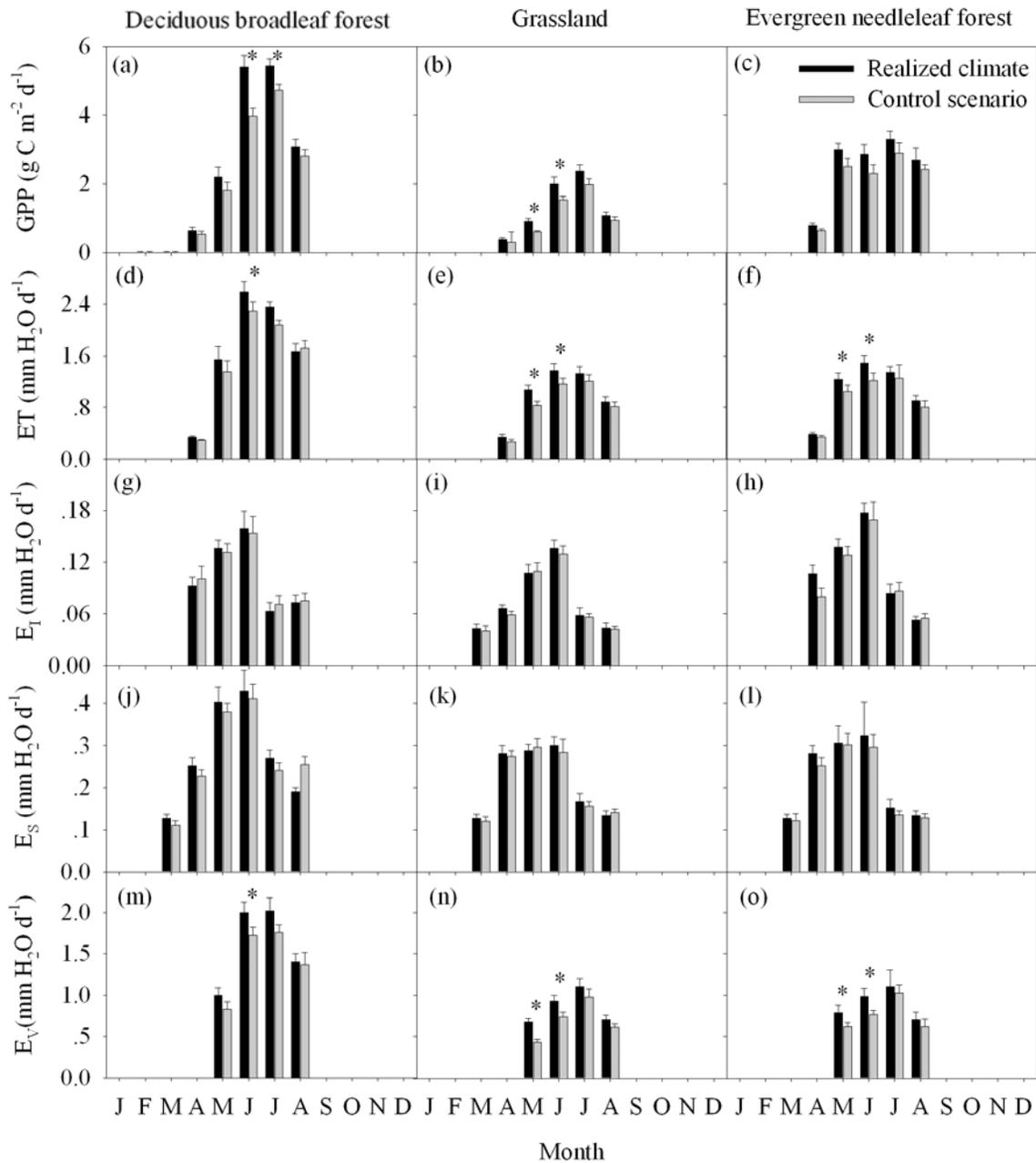


Figure 7. Comparison of (a–c) GPP, (d–f) ET, (g–i) canopy intercepted evaporation (E_1), (j–l) soil evaporation (E_S), and (m–o) vegetation transpiration (E_{V_s}) under control scenario and realized climate conditions at three ecosystems. The control scenario used the mean temperature of 2002 and 2003 to replace that of 2004 and eliminated the warming effect in realized climate conditions in 2004.

evergreen deciduous forest, and a evergreen needleleaf stand in the boreal climate zone.

[35] ET varied greatly among the three ecosystems. At the annual scales, ET was slightly higher in deciduous broadleaf forest than in evergreen needleleaf forest, and grassland showed a significantly lower annual ET compared to other two ecosystems. On average, during the medium term of growing season (June–August), ET at the deciduous broadleaf forest averaged over three study years was $1.73 \pm 0.53 \text{ mm d}^{-1}$ and was 1.22 and 1.44 times that of evergreen forest ($1.40 \pm 0.24 \text{ mm d}^{-1}$) and grassland ($1.19 \pm 0.27 \text{ mm d}^{-1}$), respectively. Our findings were the con-

sistent with those reported by *Kljun et al.* [2006], which showed a 30% higher maximum ET in boreal aspen than other conifer forests (i.e., black spruce and jack pine). The differences in leaf area index (LAI) among the three ecosystems partially explain the intrasite ET variation, and low LAI may be a major cause for small ET at the grassland site (Figure 10). In addition, other lines of evidence have supported this conclusion that ET is more conservative at conifer stands than deciduous broadleaf forests [*Baldocchi et al.*, 1997] because stomatal conductance has been observed to remain fairly constant over a wide range of VPD in the evergreen needleleaf forest

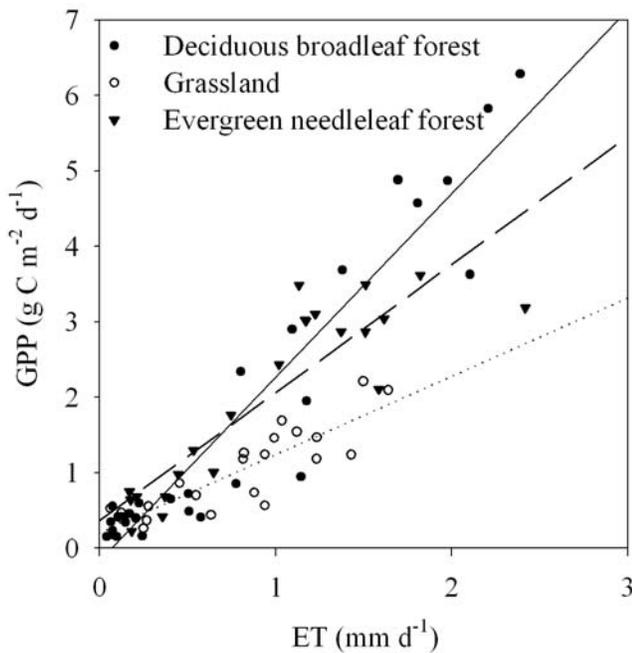


Figure 8. Relationships between GPP and ET for three sites. The regression lines from up to down were for deciduous broadleaf forest: $GPP = 2.43ET - 0.17$, $R^2 = 0.90$, $P < 0.01$; evergreen needleleaf forest: $GPP = 1.69ET + 0.37$, $R^2 = 0.80$, $P < 0.01$; and grassland: $GPP = 1.03ET + 0.21$, $R^2 = 0.73$, $P < 0.01$, respectively.

[Goulden *et al.*, 1997; Ewers *et al.*, 2005]. Deciduous broadleaf forests, in contrast, are more sensitive to conditions of high evaporative demand at the leaf level [Dang *et al.*, 1997; Hogg *et al.*, 2000].

[36] Fire disturbances significantly change ecosystem types and landscape diversity in northern regions [Kasischke and Stocks, 2000; Johnstone and Kasischke, 2005]. Higher fire frequency increases the relative abundance of early successional to midsuccessional deciduous stands compared to the older evergreen conifer stands [Chapin *et al.*, 2000; Chambers and Chapin, 2002]. Postfire succession and changes in vegetation canopy structure, litter fall, and soil properties, in turn, affect ecosystem processes that control surface energy exchange and hydrological cycles. Our study implies that fire disturbances in northern regions will lead to an increase of ET during the growing season at the regional scale due to the increasing number of deciduous stands resulting from fire disturbance.

4.2. Effects of Precipitation Seasonality on ET

[37] Precipitation seasonality appeared to be important in regulating interannual variability in ET. The three study sites showed consistent results with ET responding more sensitively to interannual variation of precipitation in the early growing season than that in the late growing season. At all three ecosystems, annual precipitation alone did not account for year-to-year variations of ET. From January to August, ET was the lowest in 2003 with a moderate annual precipitation due to precipitation deficit during the early growing season, which indicated precipitation seasonality overshadowed the function of annual precipitation to annual ET.

[38] The effect of precipitation seasonality to ET was a direct result of the seasonality of ET components that had diverse responses to precipitation. ET consists of three components: canopy interception evaporation, soil evaporation, and plant transpiration. Evaporation rates of intercepted water within the canopy and at the soil surface are fastest at the potential evaporation rate [Lankreijer *et al.*, 1999; Liu, 2001], likewise water in shallow soil also has large evaporation rates and may evaporate within days after precipitation [Heitman *et al.*, 2008]. Variation in both of these components is strongly dependent on precipitation [Liu, 2001; Heitman *et al.*, 2008]. Deep soil water, however, is mostly removed by plant transpiration, and precipitation only has an indirect effect on transpiration by regulating soil moisture and air humidity [Heitman *et al.*, 2008]. These three ET components varied widely with season due to precipitation seasonality and antecedent soil moisture content [Wu *et al.*, 1996].

[39] Model simulations showed significant decrease of intercepted water evaporation and soil evaporation due to precipitation scarcity in the early growing season of 2003. In contrast, there were not many differences in soil evaporation in July and August of 2004 compared to that of other 2 years. Model results, separating impacts of warming and precipitation seasonality under two temperature scenarios, did not show the stimulation of warming to soil evaporation in 2004 (Figures 7j–7l). Hydrological studies have demonstrated high soil moisture effectively reduced water infiltration into deep soil, reduced the impact of precipitation on transpiration, and increased the proportions of surface interception and soil evaporation [Mamedov *et al.*, 2006]. In our study, soil moisture content was normally much higher (close to saturation) in the early growing season (May and June) than in the late growing season (July and August) due to spring snowmelt and soil moisture recharge (Figure 1d), which prevented more water infiltration into the deep soil in spring. In contrast, soil moisture content was usually low in July and August, and more precipitation was infiltrated into the deep soil and sustained higher transpiration rates. Although normalized difference vegetation index (NDVI) of July was close to that of June in 2002, the specific soil moisture increase of precipitation (i.e., the ratio between the increase of water recharged into 11 cm soil and precipitation) in July was 5.7, 2.2, and 1.6 times higher than that in June at the deciduous broadleaf forest, evergreen needleleaf forest, and grassland, respectively. For instance, 1 mm of precipitation resulted in an average increase of $0.011 \text{ m}^3 \text{ m}^{-3}$ of soil moisture content in July at the deciduous broadleaf forest site, but it only resulted in an increase of $0.0019 \text{ m}^3 \text{ m}^{-3}$ in June.

[40] Precipitation scarcity in the late growing season only significantly decreased ET in the deciduous broadleaf forest, differing from the grassland and evergreen needleleaf forest (Figure 3). The deciduous broadleaf forest site might have experienced significant drought effects in the late growing season because of higher ET than other two sites during the earlier periods. Figure 11 shows that soil moisture content reached the wilting point (0.1; volumetric soil moisture content) at the deciduous broadleaf forest site in August 2004, but not at the evergreen needleleaf forest and grassland sites. Moreover, soil hydrological property also was an underlying cause leading to the response of seasonal drought.

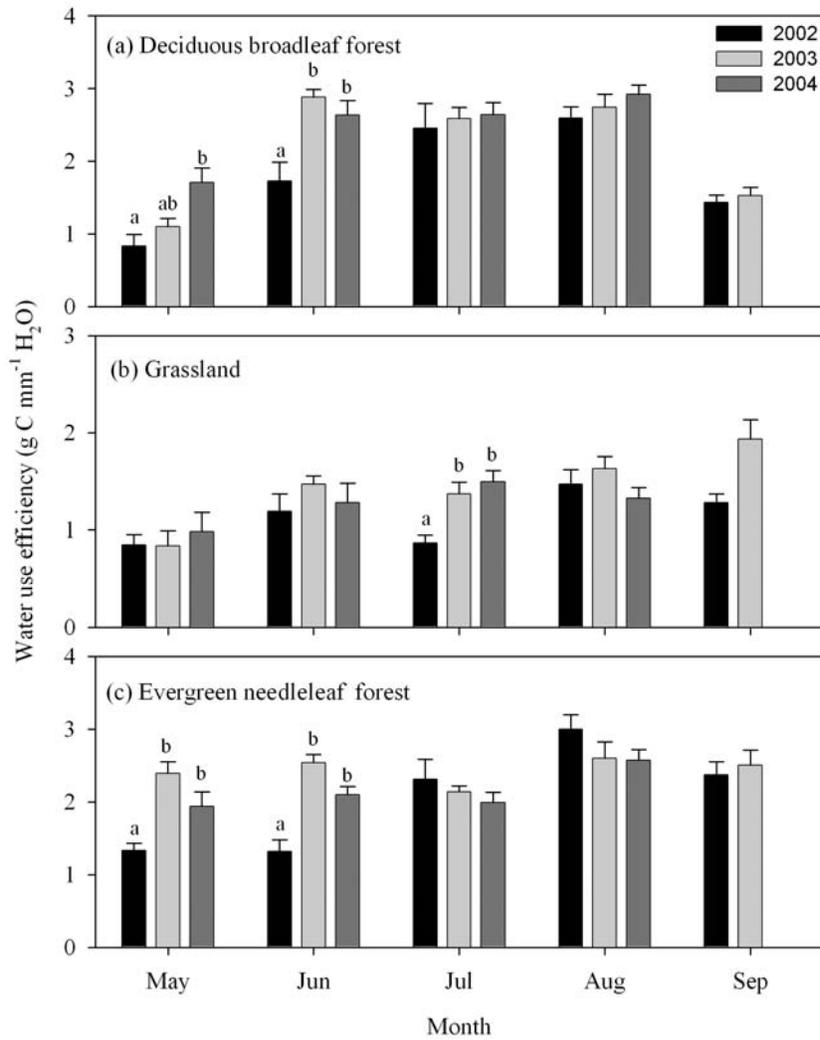


Figure 9. Monthly mean WUE during May–September from 2002 to 2004 in three study sites. Different letters indicate significant difference ($P < 0.05$) among the years.

Model analysis showed low available soil water capacity (AWC, which is the difference between field capacity and wilting point) did not have high capability to buffer water stress during long drought periods due to rapid decreases of available water content [Weng and Luo, 2008]. In this study,

AWC was lowest in the deciduous broadleaf forest, and experienced a much more serious drought.

[41] Multiple general circulation models (GCMs) have consistently shown significant increases in precipitation at high latitudes [IPCC, 2007]. As a consequence, ET is pre-

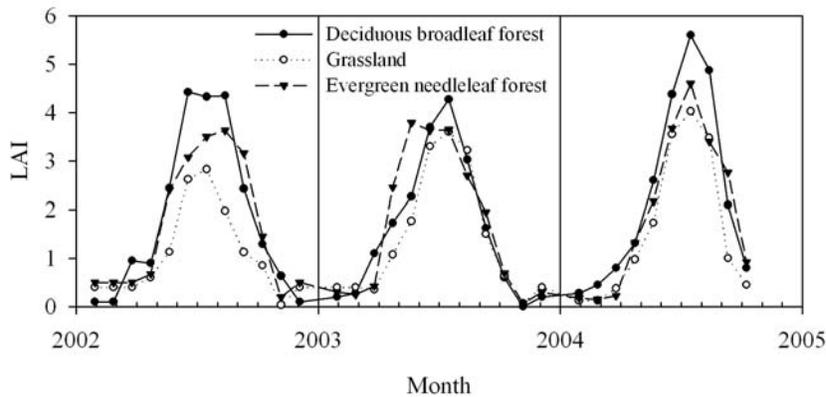


Figure 10. Monthly mean LAI in three sites. LAI is Moderate Resolution Imaging Spectroradiometer (MODIS)/Terra LAI, 1 km spatial resolution.

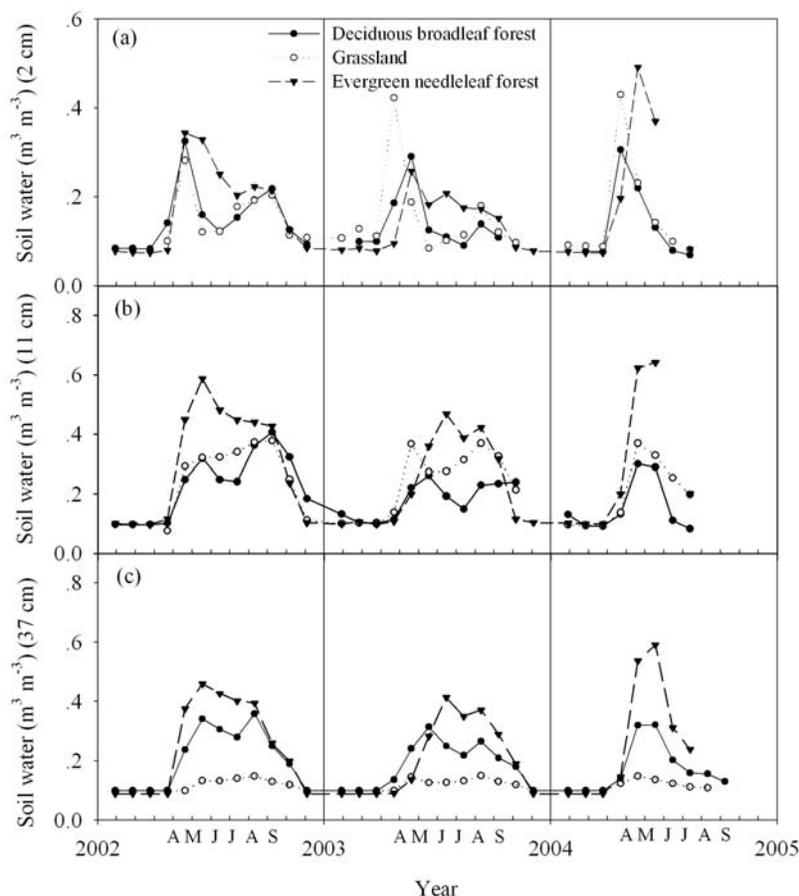


Figure 11. Monthly mean soil volumetric content of three sites measured at (a) 2 cm, (b) 11 cm, and (c) 37 cm depth.

dicted to increase under climate change, which closely balances the precipitation change [IPCC, 2007]. However, relatively few studies have considered the impacts of precipitation seasonality to ET across global and regional scales. Changes in the precipitation seasonality greatly affect the partitioning of the water into runoff, evapotranspiration, and infiltration and thus regional and global water budgets. In past decades, most of the increasing precipitation happened during autumn and winter [IPCC, 2007]. Our study suggests that if this seasonal precipitation trend holds over the future, increases in ET will be less than expected because of the lower responsiveness of ET to precipitation in the late growing season.

[42] In order to examine whether precipitation in the previous year influences the response of ET to precipitation seasonality, we conducted a model experiment to investigate the legacy effects of precipitation in the previous year on ET using IBIS. We used precipitation data of 2004 to replace that of 2002 and simulate ET variation in 2003, which made a precipitation scenario of a spring drought following an autumn drought in comparison with the realized precipitation pattern. The results did not show significant differences of ET in 2003 under this scenario compared with the realized precipitation pattern. Several major causes probably accounted for insignificant legacy effects of precipitation in previous years. Three sites have very well drained soil, and superfluous precipitation in previous years cannot retain to

the next year [Manies *et al.*, 2004]. In addition, accumulated winter snowfall will recharge soil moisture in the spring which compensates the precipitation deficit of previous years. As Figure 1d showed, over the three investigated years, soil moisture content in the early growing season approached the field capacity due to snowmelt.

4.3. Effects of Precipitation Seasonality on WUE

[43] In this study, WUE was defined as the ratio of GPP to ET at the ecosystem scale, which represents a trade-off between water loss and carbon gain in the process of plant photosynthetic carbon assimilation. Understanding the variation of WUE and its environmental control mechanisms is of great significance for estimating the effect of water status changes on the ecosystem carbon budget.

[44] Precipitation seasonality strongly affected WUE owing to asynchronous responses of GPP and ET to the seasonal variation of precipitation. Precipitation appeared to have an indirect effect on GPP by regulating soil moisture and a direct effect on ET. In May and June, when soil moisture content was sufficient, precipitation deficits in 2003 did not constrain GPP (Figure 12), but ET decreased significantly (Figure 5). Consequently, ecosystem WUE increased greatly (Figure 9). In contrast, during the late growing season of 2004, precipitation deficits had different effects in all three ecosystems. Neither GPP nor ET from the evergreen needleleaf forest and the grassland showed sig-

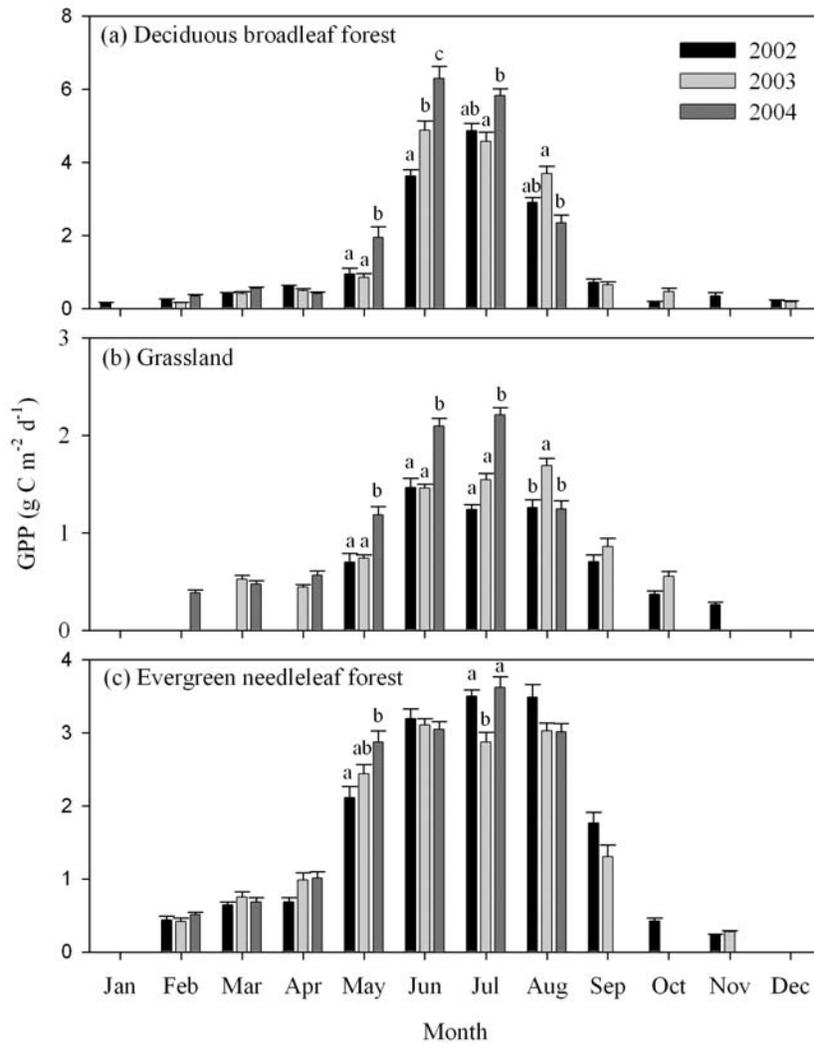


Figure 12. Monthly mean GPP from 2002 to 2004 in the three study sites. Different letters indicate significant difference ($P < 0.05$) among the years.

nificant response to reduced precipitation in the late growing season. Consequently, WUE did not differ significantly among the 3 years. Our results imply that increasing spring precipitation will induce larger water loss without a corresponding carbon gain than in summer and autumn.

[45] The higher WUE of May and June in 2004 compared to those in 2002 resulted from higher GPP and not from lower ET due to higher air temperature (Figures 8 and 9). Our modeling results showed that warming in 2004 resulted in a significant increase of GPP compared with the control climatic scenario, which used mean air temperature of 2002 and 2003 to replace that of 2004 in model simulation (Figure 7). On average, in May and June, simulated GPP were 22%, 28%, and 22% higher under the realized condition than control climatic scenario in the deciduous broadleaf forest, grassland, and evergreen needleleaf forest, respectively. Similarly, simulated ET was higher under realized condition compared to control climatic scenario with increase of 11%, 19%, and 17% in deciduous broadleaf forest, grassland, and evergreen needleleaf forest, respectively. In contrast, at the late growing season, warming did not result in the increases

of GPP and ET, which was different from warming field experiments showing that elevated temperature could stimulate ET [Harte *et al.*, 1995; Wan *et al.*, 2002]. Variation of other environmental variables (e.g., VPD or precipitation) might have overshadowed the effects of warming to ecosystem in this study. Niu *et al.* [2008] showed water stress resulted in negative impacts of the warming to ecosystem carbon and water fluxes, which implied water availability regulated the responses of ecosystem carbon and water fluxes to warming. Our results supported their observation that the warming did not enhance GPP and ET in August 2004; instead, water availability played a dominant role in determining ecosystem carbon and water fluxes.

5. Conclusions

[46] This study provided some insights into the effects of precipitation seasonality and ecosystem types on ET in the three ecosystems located in the Yukon River Basin, Alaska. Reduced precipitation in the early growing season of 2003 resulted in a substantial decrease in ET through all three

ecosystems. In contrast, drought in the late growing season of 2004 only decreased ET of the deciduous broadleaf forest, but did not decrease ET in the evergreen needleleaf forest and grassland, primarily because higher ET led to more severe soil drought, and stomata were more sensitive to soil drought in the deciduous forest than in other forests. Model simulations indicated seasonal variation of soil moisture accounted for the effects of precipitation seasonality to ET by altering the partitioning of water from precipitation events into canopy-intercepted evaporation, soil evaporation, and vegetation transpiration. Our results indicated ET was more sensitive to precipitation scarcity in the early growing season than in the late growing season. This finding implies that increases in ET will be less than expected if the current seasonal precipitation trend holds over the future with more increasing precipitation during autumn and winter.

[47] Fire disturbance plays an important role in shaping species composition and ecosystem diversity in northern regions. Postfire succession and changes in ecosystem properties, in turn, affect surface energy exchange and hydrological and biogeochemical cycles. Our results showed substantial variations of ET among ecosystems over the growing season. On average, during June and August, daily ET in the deciduous broadleaf forest, averaged over the 3 years of measurements, was $1.73 \pm 0.53 \text{ mm d}^{-1}$, and was 1.22 and 1.44 times that in the evergreen forest ($1.40 \pm 0.24 \text{ mm day}^{-1}$) and grassland ($1.19 \pm 0.27 \text{ mm day}^{-1}$). Therefore, fire disturbances in northern regions will lead to an increase of ET during the growing season at the regional scale due to the increasing deciduous stands resulting from fire disturbance.

[48] Our results illustrated some important features of WUE related to precipitation seasonality. It appeared that a precipitation shortage in spring increased WUE by decreasing ET. Precipitation shortage in the autumn did not show a significant effect to WUE in the three ecosystems. Our results implied increasing spring precipitation will induce larger evaporative water loss without a corresponding carbon gain than summer and autumn.

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