JP1.16 THE IMPACT OF SEASONAL DROUGHT ON CARBON EXCHANGE IN DIFFERENT AGED FORESTS, WASHINGTON, USA

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1. INTRODUCTION

The Pacific Northwest is one of the most productive forest regions in the world and its future role in the terrestrial carbon cycle will depend on the amount of timber harvested; in effect, how the age structure of these forests will change. This research looks at the environmental and climatic drivers of carbon and water vapor fluxes in two early seral (14 to 18 years since harvesting disturbance) and an old-growth forest (450-500 years old) in Washington State during the drought seasons 2006 and 2007. Tree physiological responses to climate extremes (e.g., drought), the timing of weather events (e.g., snowmelt, precipitation) and phenological changes (e.g., bud break) vary with age class and likely affect canopy mass and energy exchange. The young stands are less than 1.5 km from the old-growth forest, close enough to allow for a direct comparison of climatic-driving variables.

Local Disturbance History

All 3 stands are located in the Gifford Pinchot National Forest, Washington, USA, at elevations of 351m (OG), 361m (ESN) and 355m (ESS) and are classified as low elevation-Douglas fir sites in the western Cascade Mountains. The surrounding area has a highly fragmented stand age class structure due to silviculture and is characterized by large patches of even-aged coniferous forest that range in age from 65 to 150 years old, clear-cuts less than 40 years old, and interspersed remnants of older forest up to 500 years old (U.S.D.A. Forest Service, 1994).

Local Climate

Precipitation is strongly seasonal; most is confined to the winter months and a seasonal drought occurs during the summer. Since very little rain (< 5%) typically falls in the months of July and August, annual precipitation is best described for the *water-year* : *October through September*. Long-term mean annual temperature is 8.7 °C, mean minimum temperature is 2.5 °C and mean water-year precipitation is 2223 mm (Figure 1).

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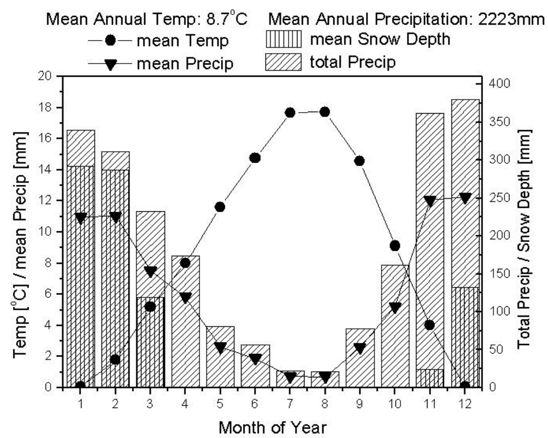

Figure 1. Nearby NOAA climate data (Carson Fish Hatchery, WA) show the distinct wet/dry seasons and the seasonal-decoupling of maximum temperature (August) and maximum precipitation (December), *in Falk (2005)*.

2. METHODS AND MATERIALS

Site Description

The Wind River Canopy Crane (45.821 N, -121.952 W) is located in the T.T. Munger Research Natural Area (Figure 2), an old-growth (OG) forest ecosystem that is composed primarily of late seral stage Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*). The forest represents the near endpoint of several gradients: age (400-500 years), biomass (619 Mg C ha^{-1}), structural vertical complexity (leaf area index = ~9 m^2 m^{-2}), and tree height (max = 65 m) (Harmon *et al.* 2004, Parker *et al.* 2004, Shaw *et al.* 2004).

The early seral north (ESN) flux tower (45.827 N, -121.960 W) was located in a recent (1994) clear-cut patch (7 ha), 1.25 km northwest of the canopy crane (Fig 2). This stand represents a third generation Douglas-fir forest: the original old-growth forest was logged in 1920 and a clear-cut harvest was done in 1994 on the 80-year old Douglas-fir trees. In 1997, the stand was seeded with Douglas-fir saplings. Tree height and diameter at breast height (dbh) was measured in September 2005 (mean = 4 m, range = 1.2 to 5.3 m, mean dbh = 5.7 cm).

The early seral south (ESS) flux tower (45.813 N, -121.959 W) was located in an abandoned clear-cut (1990), 1.1 km southwest of the canopy crane (Fig 2) and was naturally established with Douglas-fir (the pioneering species) from surrounding cone crops. In July 2007 the average DF tree height was 3.58 ± 0.84 m and dbh was 4.47 ± 1.6 cm (n=95 trees). The estimated tree density was 1063 trees/hectare (biomass survey included 7 plots X 100 m^2). Tree coring revealed that stand-representative Douglas-fir trees were between 9 and 12 years of age in 2007 (n=10 trees).

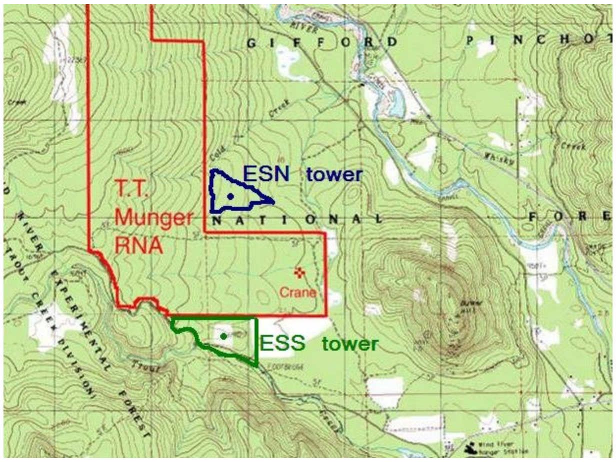

Figure 2. Site locations of the canopy crane (T.T. Munger RNA old-growth forest) and early seral stands and flux towers.

Canopy Crane Instrumentation

The eddy-covariance (EC) system consisted of a closed path Infrared Gas Analyzer (LiCor 6262) and an ultrasonic anemometer (Gill HS), both mounted at 70 m on an 87 m tall canopy crane. The EC system measured CO_2 and H_2O vapor mixing ratios and turbulent wind velocities at 10 Hz. Soil moisture was measured with a time domain reflectometry (TDR) system (CSI TDR100, 6 CS610 probes) at integrated depths of 0 to 2 m. Soil temperature (3 CS 107B probes) was measured at depths of 0, 15, 30 cm. Additional meteorological instrumentation included a 4-stream net radiometer (Kipp and Zonen CNR-1), up- and down-facing PAR sensors (LiCor 190SB), air temperature/humidity sensor (HMP35C) and barometric pressure sensor (Vaisala CS105). EC flux and meteorological measurements were taken for this project from January 2006 through December 2007 (Table 1).

Early Seral (ES) Instrumentation

Eddy-covariance estimates of vertical H_2O and CO_2 fluxes were made at both early seral stands using a CSAT-3 sonic anemometer (Campbell Scientific, Logan, Utah, USA) and an open-path fast response (LiCor 7500, LiCor, Lincoln, Nebraska, USA) Infrared Gas Analyzer which measured the velocity vectors, sonic temperature, and the densities of CO_2 and H_2O vapor at 10 Hz. All raw data were archived, in the field, using a CR1000 data logger (Campbell Scientific, Logan, Utah, USA) and 1 GB storage card, and downloaded weekly onto a laptop computer.

At ESN, the sonic anemometer was mounted facing west-southwest, 260º, pointing in the direction of greatest homogeneous fetch (200 m from the western stand edge). Both the LiCor-7500 and CSAT-3 were mounted at 5.5 m a.g.l., 1.5 m above the ESN canopy, on a boom extending from a 6m tall tower. Tower-based meteorological data included half-hourly measurements of air temperature/relative humidity (HMP-35C, Vaisala, Inc., Oy, Finland), net radiation (REBS Q7), soil temperature (5, 10 and 15 cm) (CS106B, Campbell Scientific, Logan, Utah, USA) and soil water content (0-30 and 30-60 cm) (Time-domain reflectometry (TDR) system, TDR100, Campbell Scientific, Logan, Utah, USA). EC flux and site meteorological data were collected at ESN from March through October, 2006 (Table 1).

At ESS, the sonic anemometer was mounted in the southerly direction to reduce the frequency of tower-shading: valley flow produced winds that occurred 50% of the time from the west and 50% of the time from the east. Both the LiCor-7500 and CSAT-3 were mounted at 5.0 m a.g.l, 1.5 m above the ESS canopy. Tower-based meteorological data included half-hourly measurements of air temperature/relative humidity (HMP-35C, Vaisala, Inc., Oy, Finland), net radiation (REBS Q7), up- and down-facing PAR sensors (LiCor 190SB), soil temperature (5, 10 and 15 cm) (CS106B, Campbell Scientific, Logan, Utah, USA) and soil water content (0-30, 30-60, 60-90 cm) (Time-domain reflectometry (TDR) system, TDR100, Campbell Scientific, Logan, Utah, USA). EC data at ESS were collected March through August 2007 and meteorological data through October 2007 (Table 1).

Flux calculations and Corrections

Old-growth Canopy Crane

Carbon dioxide (μmol CO_2 m^{-2} s^{-1}), water vapor (mmol H_2O m^{-2} s^{-1}) and energy (W m^{-2}) fluxes were computed with FORTRAN90 code using a 30-minute averaging period and a horizontal coordinate rotation. Half-hourly CO_2 fluxes were further screened for outliers and gap-filled for missing values (using a running-mean approach, Reichstein *et al.* 2005). For further details on post-processing see Paw U *et al.* (2004) and Falk (2005).

Early seral flux towers

At the two early seral stands, CO_2, H_2O and energy half-hour fluxes were calculated including the Webb et al. 1980 (WPL80) density corrections with the CR1000 eddy covariance program (Campbell Scientific) so that data could be quality-controlled in real-time. During post-processing, all scalar and energy fluxes were corrected so that the mean cross-wind (vbar) and vertical wind (wbar) velocities were rotated to zero (following the natural wind coordinate system). Half-hour scalar and energy fluxes were quality controlled for non-preferred wind directions, inadequate turbulence (based on unrotated wbar/TKE and ubar/TKE ratios), heavy precipitation events, and times of general instrument failure. Missing scalar and energy fluxes were gap-filled using a running-mean approach (Reichstein *et al.* 2005).

	ESN	OG06	ESS	OG07
Flux measurement period	Mar 27-Oct 25, 2006	Jan 1-Dec 31 2006	Apr 14 - Aug 31, 2007	Jan 1-Dec 31 2007
Meteorological measurement period	May 3-Nov 11, 2006	Jan 1-Dec 31 2006	Apr 26 – Oct 25, 2007	Jan1 - Dec 31 2007
% Missing or excluded flux data	40%	55%	29%	34%
% Missing met data	20%	1%	5%	1%
EBC % (R^2)	81% (0.92)	76%	80% (0.89)	74%

Table. 1. Data availability and energy budget closure (EBC) at each flux tower.

Bulk Canopy and Mechanistic Variables

All mechanistic and bulk canopy variables were calculated for daytime (K_{in} > 10 W m^{-2}) half-hour periods only. Equilibrium evapotranspiration (E_{Teq}), a measure of the climatologically expected E_T over a moist surface based on temperature and available energy only, was calculated from McNaughton and Spriggs (1986):

$$E_{Teq} = (\frac{\Delta}{\Delta + \gamma})(Rn - G) \quad (1)$$

In Eqn 1, Δ is the slope of the saturation vapor pressure curve (kPa K^{-1}) and γ is the psychrometric constant (kPa K^{-1}). Potential evapotranspiration, E_{To}, was calculated from 1.26 * E_{Teq}.

The Priestly-Taylor coefficient, α, indicates the degree of soil water supply limitation on E_T and was calculated using Eqn 2 (Priestly and Taylor 1972).

$$\alpha = \frac{E_T}{E_{Teq}} \quad (2)$$

Following Stewart (1988), canopy conductance (g_c) was calculated using the inverted Penman-Monteith equation:

$$\frac{1}{gc} = \frac{\rho c_p \delta e}{\gamma LE} + \frac{\frac{\Delta}{\gamma}\beta - 1}{ga} \quad (3)$$

In Eqn 3, g_c is canopy conductance (m s^{-1}), ρ is air density (kg m^{-3}), c_p is specific heat (J kg^{-1} K^{-1}), δe is vapor pressure deficit (kPa), LE is latent energy (J m^{-2} s^{-1}), β is the bowen ratio (sensible heat flux to latent heat flux ratio), and g_a is aerodynamic resistance (m s^{-1}).

A decoupling factor, Ω, was calculated based on Jarvis and McNaughton (1986) (Eqn 4). Ω is a unitless number and ranges from 0 to 1 depending on whether E_T is controlled strongly by canopy conductance and VPD (Ω will approach zero) or whether it is dominated by available energy to the canopy (Ω will approach 1).

$$\Omega = \frac{\varepsilon + 1}{\varepsilon + 1 + \frac{ga}{gc}} \text{; where } \varepsilon = \frac{\Delta}{\gamma} \quad (4)$$

A water use efficiency (WUE) expression was modified to represent the amount of net carbon uptake (g C) for every kilogram of water lost by the ecosystem from evapotranspiration (Eqn 5).

$$WUE = \frac{NEE}{E_T} \quad (5)$$

3. RESULTS AND DISCUSSION

Climate and Stand Microenvironments

Water-year precipitation was 2361 mm in Oct 2005-Sept 2006 and 2129 mm in 2006-2007. Although the water-year totals were relatively equal, the seasonality of precipitation varied amongst years. 2006 was a wet spring (409 mm) while March through June in 2007 received just half the precipitation (217 mm). Summer (July-October) rains also varied dramatically: 72 mm (2006) and 316 mm (2007). Overall, 2006 had a wetter and cooler start to the very dry drought season, while 2007 received relatively little rain in the spring but periodic rain events throughout the summer (fig 3).

As expected the ES stands were warmer on most summer days than the dense old-growth forest (shown for soil temperature in figure 3). Soil water content (θ_v) also varied among stands and years although the drought seasonal pattern remained a dominant feature. In 2006, the near-surface θ_v was similar at both ESN and OG: after June 2006, soil moisture continued to decrease and approached 0.15 m^3 m^{-3} until rains returned in October. At ESS, θ_v never dropped below 0.20 m^3 m^{-3} while it approached 0.15 m^3 m^{-3} at OG. The additional measurement depths in 2007 revealed that while near-surface θ_v at OG becomes limiting, deeper water reserves never dropped below 0.3 m^3 m^{-3}.

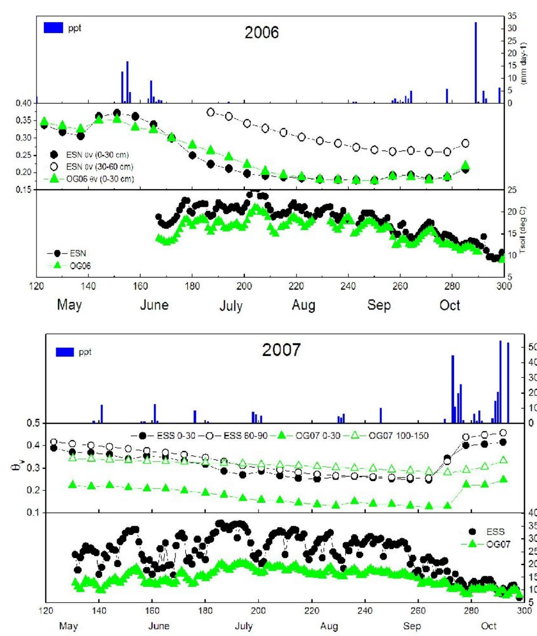

Figure 3. Precipitation, soil moisture and soil temperature data at ESN and OG in 2006 and ESS and OG in 2007.

Carbon and Water Exchange

Peak daytime latent heat (LE) fluxes were relatively constant at the OG stand no matter the month with an exception of a LE decline in July. On the other hand, distinct seasonal LE fluxes were observed at the early seral stands. Maximum LE occurred during the summer while spring values were relatively low. Also, peak LE fluxes (and hence E_T) were nearly twice as great at ESN than at OG, while a smaller increase over OG07 was seen at ESS (fig 4).

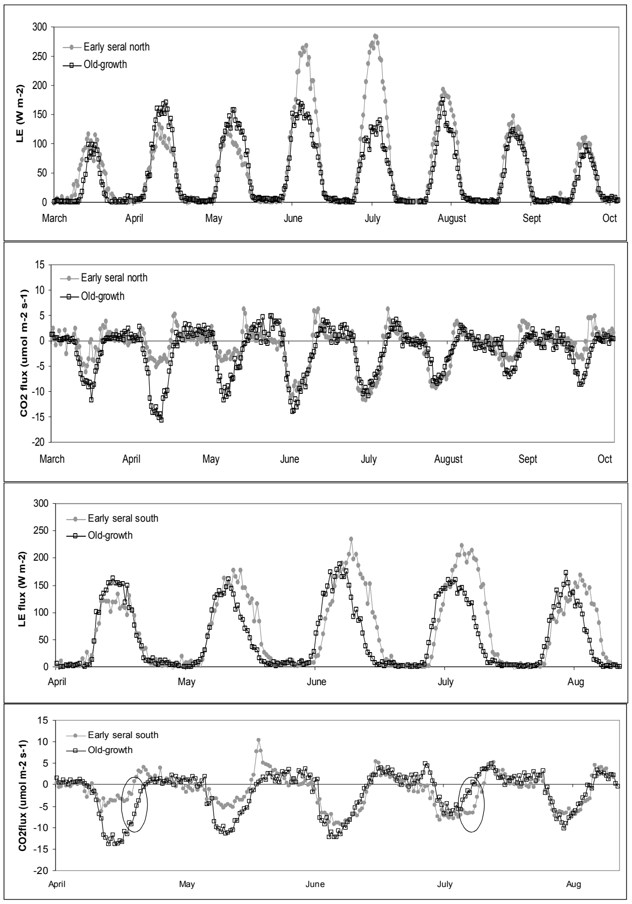

Figure 4. Mean monthly diurnal latent heat and CO_2 fluxes at ESN and OG in 2006 and ESS and OG in 2007.

Figure 4 also shows that maximum net carbon dioxide uptake occurred in April at the old-growth stand when midday fluxes approached - 15 umol m^{-2} s^{-1} in both 2006 and 2007. Net CO_2 uptake declined during the summer months at OG. In contrast, maximum net CO_2 uptake occurred during June at both ESN (-12 umol m^{-2} s^{-1}) and ESS (-13 umol m^{-2} s^{-1}), while April fluxes were approximately only -5 umol m^{-2} s^{-1}.

A time lag (~ 2 hr) occurred between peak daytime CO_2 and LE fluxes at ESS and OG07 but not at ESN and OG06. The time lag created a longer period of net CO_2 uptake in April for the old-growth stand but a much reduced period at OG during the summer months (see circled periods in figure 4)

Indications of Water Stress on Gas Exchange

The old-growth stand had higher water use efficiency (3 to 4 g C kg H_2O^{-1}) than both early seral north (2 to 3 g C kg H_2O^{-1}) and south (1 to 2 g C kg H_2O^{-1}) during all months. The Bowen ratio was also consistently higher at the old-growth stand indicating that more available energy was transferred into sensible heat at OG than at ESN and ESS. Canopy conductance rates at each stand decreased as the drought season progressed, coinciding with increasing VPD and decreasing θ_v. The decoupling factor also decreased during the drought season in 2006 at ESN and OG (this was a very dry summer) and approached values of 0.10 before the start of autumn precipitation. The summer of 2007 had continuous precipitation and a decline in Ω was not observed at the old-growth stand in 2007; and instead, the decoupling factor was higher than the previous year.

	ET/E_{To}	WUE	Ω	g_c	β
ESN June	0.55	2.5	0.21	9.4 ± 3.1	0.9 ± 0.5
ESN Sept	0.39	2.1	0.12	7.9 ± 3.5	1.6 ± 0.8
OG06 June	0.32	4.2	0.27	7.9 ± 3.7	2.1 ± 1.3
OG06 Sept	0.26	4.3	0.15	4.3 ± 3.2	1.9 ± 1.1

Table 2. Canopy parameters for selected months at ESN and OG in 2006.

	ET/E_{To}	WUE	Ω	g_c	β
ESS May	0.44	1.6	0.15	6.1 ± 3.0	1.3 ± 0.6
ESS July	0.54	1.5	0.16	5.4 ± 2.1	0.94 ± 0.7
OG07 May	0.34	4.3	0.31	6.2 ± 4.3	2.6 ± 1.5
OG07 July	0.35	3.2	0.31	5.0 ± 3.4	2.2 ± 1.4

Table 3. Canopy parameters for selected months at ESS and OG in 2007.

In general, the old-growth stand had a higher decoupling factor than the early seral stands (tables 2 and 3). The monthly decoupling factors in 2007 indicate that gas exchange in the ESS canopy is more coupled to VPD than at the old-growth stand, although VPD appears to be strongly limiting CO_2 uptake in the older trees (fig 5), especially on summer afternoons.

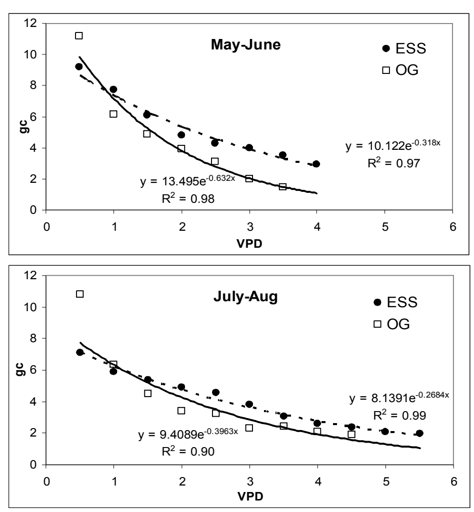

Figure 5. Mean midday g_c by vapor pressure deficit bin at ESS and OG in 2007.

A closer look at canopy conductance revealed site differences in leaf-atmosphere gas exchange in response to water stress. At low VPD (< 0.5 kPa) the OG stand had higher g_c than the young stands but beyond values of 1 to 1.5 kPa, g_c at OG rapidly declined with increasing VPD (fig 5) even as soil moisture was not limiting. In general, g_c was lower in July and August than in May and June but the drought season decrease was more dramatic at OG.

Mid-summer canopy conductance rates decreased earlier in the day at the old-growth forest than at ESS and to a lesser degree at ESN (Fig 6), indicating greater stomatal closure in the 50 to 60 m tall Douglas-fir trees than the 4 m trees.

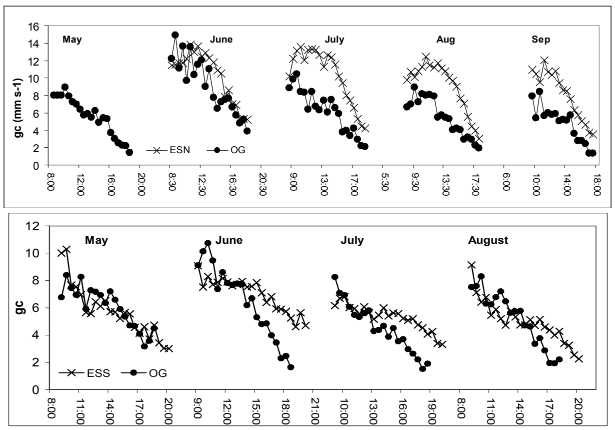

Figure 6. Mean daytime canopy conductance rates by month and site.

The canopy conductance rates at OG07 and ESS explain why E_T and CO_2 exchange peaked later in the day at the younger stand (fig 4). VPD was almost always lower in the old-growth forest than in the early seral stands so the stomates are generally closing at lower VPD levels in the older trees. Stomatal closure was induced at moderate to high VPD regardless of soil moisture because tall Douglas-fir trees at Wind River have access to deep (2 m) water supplies (Domec *et al.* 2004) and OG soil moisture never dropped 0.30 $m^3\ m^{-3}$ at the 1 m depth in 2007.

4. CONCLUSIONS

Age (and height) response differences in ecosystem exchange to seasonal drought were observed in this study. The old-growth forest took advantage of high light levels and low VPD in the spring by having maximum net carbon uptake rates. During the summer, the old-growth stand maintained a high WUE by inducing stomatal closure even under moderate VPD levels to limit transpiration. In contrast, the early seral stands had the highest net carbon uptake during the summer but also had high rates of evapotranspiration. Even with higher CO_2 uptake, this water loss created lower WUE in the early seral stands during the summers. As near-surface soil moisture declined throughout the summer, the early seral stands could not maintain high E_T rates and CO_2 uptake was eventually reduced in late summer as canopy conductance rates also decreased.

Here we showed that there are age-specific and seasonal-specific feedbacks between canopy conductance, vapor pressure deficit, evapotranspiration and soil moisture. Old, tall trees in the Pacific Northwest have adapted to the long drought season by increasing net carbon uptake in the spring months before VPD levels become high. Under even moderate VPD, foliage at the tops of tall Douglas-fir trees reach near critical values for cavitation due to a long path distance between the water table and the hydraulic capacity of the xylem, and as a result, shut their stomata frequently (Ryan and Yoder 1997). Shorter, younger trees at Wind River have seasonal fluxes more similar to temperate deciduous forests than mature evergreen conifer forests and maximum net carbon uptake coincides with the termination of bud break (June) and increased LAI. Young stands will be more susceptible to water stress during extreme drought due to their limited root system (i.e., lack of access to deeper water) and their slow response-time for inducing stomatal closure and conserving water under moderate levels of VPD.

5. ACKNOWLEDGEMENTS

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