3.6 THE IMPACT OF WATER STRESS ON CARBON EXCHANGE IN TWO CONTRASTING STAND-AGE CONIFEROUS FORESTS OF THE PACIFIC NORTHWEST

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1. INTRODUCTION

Eddy covariance measurements of carbon, water, and energy fluxes have been taken at the Wind River Canopy Crane Research Facility (WRCCRF), over an old-growth (OG) coniferous forest, since March 1998 and more recently at an early seral (ES) conifer stand since August 2005. The second tower was added to increase our understanding of regional Douglas-fir forest response to short-term fluctuations in climate, including seasonal drought stress. Physiological responses to climate extremes and timing of climatic events (e.g., snowmelt, precipitation) and phenological events (e.g., winter dormancy) may vary with age class and affect NEE. The young stand is 1.25 km from the old-growth forest, close enough to allow for a direct comparison of climatic-driving variables. The response of net ecosystem exchange of carbon (NEE) at the young stand during the seasonal drought may be very different from that of the old-growth forest due to differences in canopy structure, creating site differences in soil moisture and soil temperature. How this affects carbon uptake at both stands is one of the questions that will be addressed by this study.

Earlier research of a 20-year old Douglas-fir forest at Wind River (Brooks et al., 2002) found that the effects of summer drought in the forest were partially muted by hydraulic redistribution (established trees are able to lift water from deeper, moist soil horizons and release it into shallower, drier soil portions) which accounted for an additional 16 days of stored water to remain in the upper soil horizons after a 60-day drought. Early seral forests (~10 years old), are not expected to have the necessary root system to reach these deep water reserves during the dry summer months and may be more sensitive to water stress than older forests in the region.

Regional Disturbance History

Both stands are located in the Gifford Pinchot National Forest, Washington, USA, at elevations of 351m (OG) and 361m (ES), and are classified as low elevation sites in the western Cascades. The surrounding area has a highly fragmented stand age class structure due to logging 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).

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Long-term Climate

Precipitation is strongly seasonal; most is confined to the winter months and a seasonal drought occurs during the summer. Very little rain (< 5%) falls in the months of July and August, with several months on record having no measurable precipitation (most recently in 2003). Annual precipitation is best described for the water year: August through July the following year. 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).

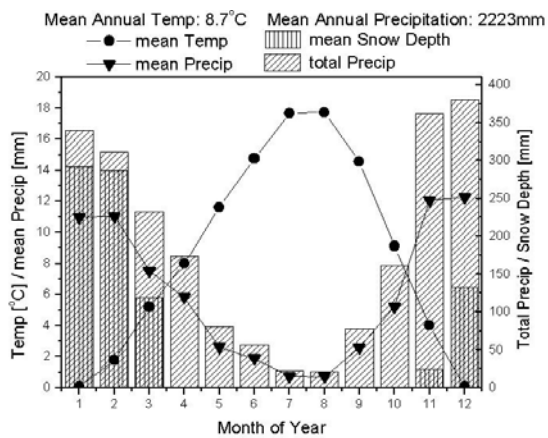

Figure 1. Nearby NOAA climate data (Carson Fish Hatchery, WA) show the distinct wet/dry seasons and the time-decoupling of maximum temperature (August) and maximum precipitation (December), *in Falk (2005).*

The most productive Douglas-fir forest ecosystems in the Cascades are low-elevation stands, which are assumed to be relatively insensitive to climate when compared to subalpine species, but Hessl and Peterson (2004) caution that Douglas-fir may be more sensitive to climate perturbations on drier sites at any elevation. The Wind River OG and ES stands are at the drier end of the current climate gradient for low elevation Douglas-fir forests. Consequently, the ES and OG flux towers provide a unique basis for evaluating the impact of summer water stress on forest carbon exchange in a region that is predicted to have more extreme and prolonged drought periods.

Objectives

Our objectives in this study are to: (1) Gain continuous eddy covariance flux measurements of carbon, water, and energy, and meteorological measurements of air temperature, soil temperature, PAR, VPD, and soil moisture at both aged stands. (2) Identify the environmental controls on NEE at both stands and identify any differences in the sensitivity of NEE to weather anomalies during the growing season and summer drought months. (3) Identify and contrast the time lags between specific environmental variables (e.g., soil moisture, soil and air temperature, VPD, PAR) and NEE at both aged stands to identify any significant differences.

Hypotheses

(1) Net primary productivity of both stands is limited by soil water availability. (2) Net ecosystem exchange is more sensitive to weather perturbations at the early seral stand, largely due to the mature forest having a moderated soil and canopy microclimate. (3) A more severe and/or prolonged seasonal drought will have a greater impact on net carbon uptake in the early seral stand due to greater reductions in soil moisture availability and higher, within-canopy vapor pressure deficit (VPD).

2. METHODS AND MATERIALS

Site Description

The WRCCRF (45.821, -121.952) is located in the T.T. Munger Research Natural Area (Figure 2), an old-growth forest ecosystem that is composed primarily of late serial 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 ha-1), structural complexity (two-sided leaf area index = ~9 m2 m-2, estimates ranging from 6.3 to 12.3), maximum tree height at 65 m and 437 trees ha-1 (Harmon et al., 2004, Parker et al., 2004, Shaw et al., 2004). The early seral flux tower (45.827, -121.960) is located in a recent (1994) clear-cut patch (7 ha) and composed primarily of Douglas-fir (*Pseudotsuga menziesii*) saplings of 4m average height.

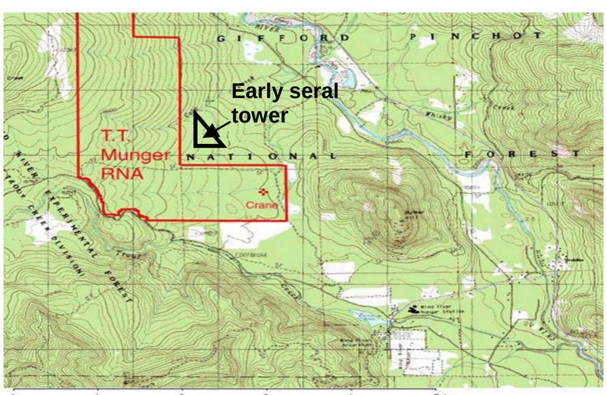

Figure 2. Site locations of the old-growth forest (T.T. Munger RNA) and early seral stand (indicated by the triangle) and the corresponding placement of flux towers within each stand. The younger forest is 1.25 km northwest of the canopy crane. The old-growth forest and early seral stand are separated by a buffer zone of 80-year old Douglas-fir trees. Maximum fetch in both stands is in the westerly direction, which is the dominant wind direction.

Old-growth Site 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 canopy crane and has been operating continuously since March 1998. The EC system measured fluxes of CO_2, H_2O, and turbulent velocities at 10 Hz. Fluxes were calculated over a 30-minute averaging time using a horizontal rotation. Soil moisture was measured with a time domain reflectometry (TDR) system (CSI TDR100, 6 CS610 probes) at integrated depths of 0-300mm. 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).

Early Seral Site Instrumentation

The EC system consisted of an open path Infrared Gas Analyzer (LiCor 7500) and a 3-D sonic anemometer (CSAT3) both mounted at 5.75m on a 6m tall tower and has been operating since August 2005. In April 2006, soil moisture and soil temperature instrumentation were added, including a TDR system (CSI TDR100, 4 CS610 probes) and a thermocouple (Omega Type "T") profile at soil depths of 5, 15, and 30cm. Additional meteorological instrumentation included an air temperature/humidity sensor (HMP45C), net radiometer (Q7) and downfacing PAR sensor (LiCor Pyranometer).

3. RESULTS

Stand Microclimatic Differences

We measured snow-depth as an indicator for canopy interception differences between stands. During one event, the average snow-depth was 20 cm within the early seral stand and 5 cm within the old-growth canopy. Additional meteorological data in 2005 from stations within and outside of the old-growth forest show a moderated microclimate within the deep forest canopy (Figure 3).

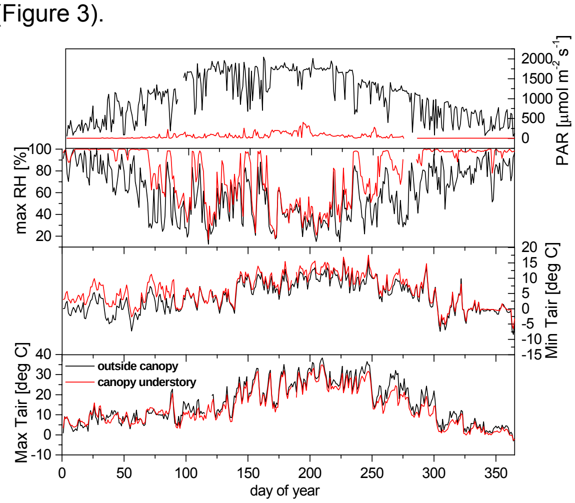

Figure 3. The 70m tall old-growth canopy has a

moderated microclimate as shown by the understory meteorological station. The complex vertical canopy structure of the old-growth forest suppresses frost damage during the winter months and extreme temperature and dryness during the summer months.

Dry Season Water Availability

Soil moisture data are currently available at the old-growth stand and will be available at the early seral stand starting in April for analysis of NEE-drought response during the 2006 dry season.

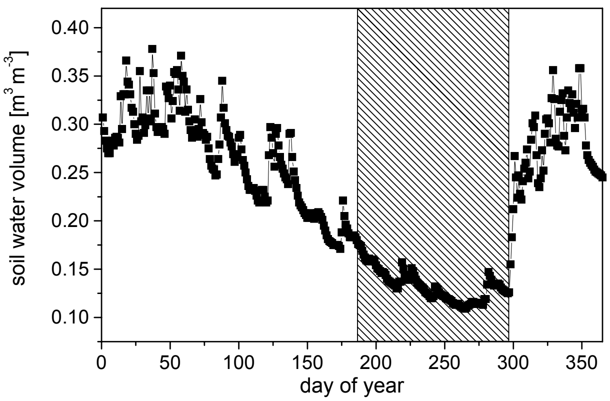

Figure 4. Typical soil moisture time series plot for the old-growth forest ecosystem. The drought period, indicated by the shaded region, lasts on average 103 days, with a range of 54-126 days.

The historical climate record shows that summer rainfall can vary anywhere between 0 to 275 mm. Variability in summer rainfall may be increasing, as indicated by data from recent years (Figure 5).

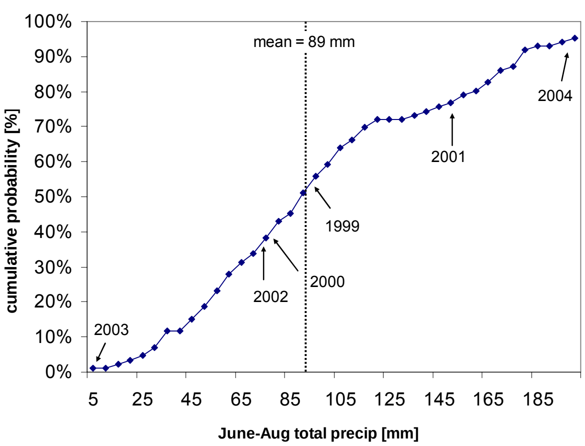

Figure 5. Cumulative probability plot of summer rainfall based on 1919-2004 data. The recent variability has been especially high with a record low observed in 2003 and a near record high measured in 2004.

Carbon Dioxide Flux

Eddy covariance data were collected at the end of the seasonal drought at both stands. Flux measurements showed differences in carbon sink/source activity between the different aged forests: the old-growth stand was a net carbon sink (-0.33 gC m^{-2} day^{-1}) while the early seral stand was a net carbon source (+2.4 gC m^{-2} day^{-1}) to the atmosphere.

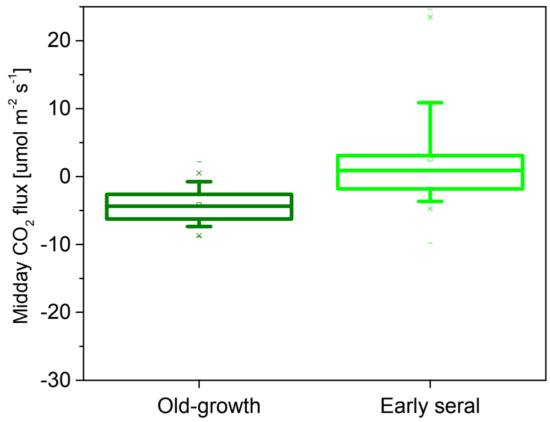

Figure 6. Dry season recovery period: statistical plot of midday carbon dioxide fluxes at the old-growth and early seral stands in October. Average (median) CO_2 flux at the OG stand was -4.2 μmol m^{-2} s^{-1} (-4.4 μmol m^{-2} s^{-1}) and at the ES stand was +2.6 μmol m^{-2} s^{-1} (+1.0 μmol m^{-2} s^{-1}).

Continuous collection of fluxes at this tower began again in early March 2006 and showed reduced midday (10 a.m. - 2 p.m.) carbon uptake at the early seral stand in comparison to the old-growth forest ecosystem (Figure 7, significant at $P<0.0001$). Nighttime fluxes were slightly more positive at the younger forest, possibly from increased heterotrophic respiration of residual site disturbance carbon pools at the early seral stand (Figure 8). Daily NEE during the growing season at the OG stand was -1.97 gC m^{-2} day^{-1}, while the younger stand was a slight source, + 0.31gC m^{-2} day^{-1}.

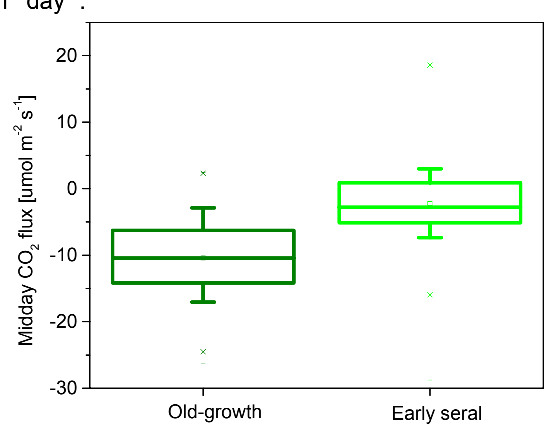

Figure 7. Wet season/growing season period: statistical plot of midday carbon dioxide fluxes at the old-growth

and early seral stands in March. Average (median) CO_2 flux at the OG stand was -10.4 µmol m-2 s-1 (-10.4 µmol m^{-2} s^{-1}) and at the ES stand was -2.2 µmol m^{-2} s^{-1} (-2.8 µmol m^{-2} s^{-1}.

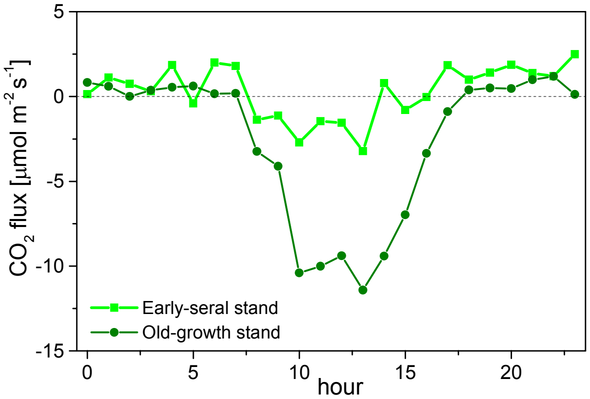

Figure 8. Wet season/growing season period: hourly carbon dioxide flux measurements at the both stands in March show reduced daytime carbon uptake at the early seral stand as compared to the old-growth forest ecosystem.

The early seral stand had lower carbon uptake rates during both the dry season recovery period and growing season than the older forest. The largest differences between stand fluxes were observed during the midday hours.

Indications of Water Stress on Carbon Fluxes

For very high summer temperatures at the old-growth stand, there is no or very little positive correlation between PAR and carbon uptake. In the dry summer months from July to August daytime NEE is limited at high vapor pressure deficit (VPD) in combination with limited soil moisture availability, resulting in stomatal shut-down on the leaf level. Figure 9 shows that high VPD (> 2.5 kPa) levels in the OG stand result in positive NEE for high PAR, indicating overall carbon loss. Further analysis revealed that OG carbon fluxes show indications of water stress at soil moisture measurements less than 0.2 m^3 $m^{-3.}$

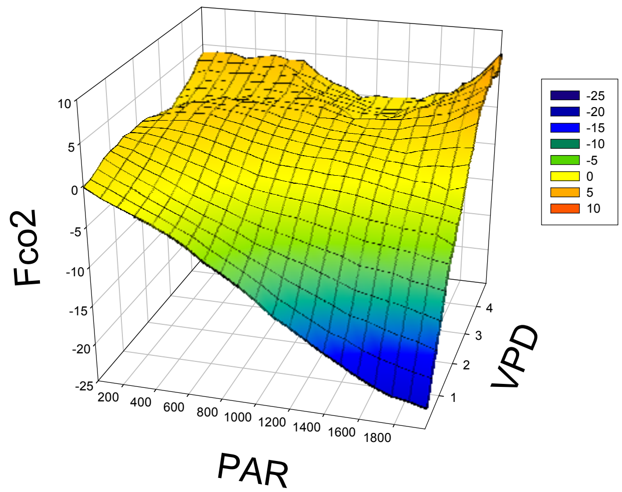

Figure 9. 3-dimensional response surfaces for CO_2 flux, PAR, and VPD at the old-growth forest in 2003. The color scale corresponds to carbon dioxide fluxes in µmol m^{-2} s^{-1}.

4. DISCUSSION

Age response differences in ecosystem exchange have also been observed by Chen et al. (2002, 2004) during a chronosequence study of the Wind River old-growth forest and nearby 40 year- and 20 year-old Douglas-fir stands. In that study the 40 year-old forest was a stronger net carbon sink than the old-growth forest, possibly due to rapid growth of the younger forest ecosystem.

Older Douglas-fir forest ecosystems have a closed canopy and are somewhat buffered from extreme summer drought stress due to moderated microclimates and deep root structure. Even so, in this study we observed that carbon exchange at the older forest can be impacted by moisture stress if concurrent with high temperature and high VPD. Since early seral stands experience a harsher, drier microclimate than older, established Douglas-fir forests, these young stands are expected to be more sensitive to climate extremes, including summer drought. We will continue to study the impact of water stress on both stands as the 2006 dry season develops.

5. ACKNOWLEDGEMENTS

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