3.3 Interannual variability of water use efficiency in an old-growth forest under drought conditions

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1. INTRODUCTION

One traditional forest ecological paradigm predicts that after serious disturbance (fire, clear cutting, etc.) forest systems start as a strong carbon source (to the atmosphere), that shifts into a strong sink after a few years, peaking after some decades, then declining as a sink until reaching carbon equilibrium (Odum, 1965, DeBell and Franklin, 1987; Franklin and DeBell, 1988; Melillo et al., 1996; Schulze et al., 1999). Conversely, some studies have demonstrated that older ecosystems under favorable climate conditions continue to be significant carbon sinks (Grier and Logan, 1977; Turner et al., 2000; Carey et al., 2001; Paw U et al., 2004). The widely-held assumption that young forests represent significant sinks of CO_2 is based on their rapid stem growth (Houghton 1983, Wofsy et al., 1993, Birdsey et al., 1993, Heath and Birdsey 1993, Turner et al., 1995, Schimel et al., 1996, DeLucia et al., 1999), after the initial seedling establishment period of several years when it is a carbon source (while residual biomass of the preceding forest is decomposed). Suggestions have been made that the CO_2 content of the atmosphere could be reduced if slowly growing old-growth forests were converted to faster growing, younger, intensively managed forests (Banuri et al., 2001). The regional implications of variation in carbon and water exchange, derived from limited surface data (e.g., a flux sites), is critical for identifying and quantifying the role of terrestrial ecosystems in climate change and the converse, the effect climate change on terrestrial ecosystems.

Continuous eddy-covariance carbon flux measurements have been made at the Wind River Canopy Crane Research Facility (WRCCRF) since 1998, a 500 year old coniferous temperate rain forest in southern Washington. The data show exceptionally high interannual variability in atmosphere-ecosystem carbon exchange. Within the AMERIFLUX/FLUXNET network this site represents a unique ecosystem and the endpoint of several gradients: age (~500 yr), aboveground biomass (619 Mg ha^{-1}), and structural complexity (two-sided leaf area index = 7-12, tree tops at 65 m, and 427 trees ha^{-1}) (Harmon et al., 2004, Parker et al., 2004, Shaw et al., 2004).

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In this paper we focus on the relationship between water availability and carbon sequestration. While this old-growth has a high biomass it experiences regular summer drought. Our observations show that the seasonal rain-forest can assimilate carbon at relatively high rates (2.1 MgC ha^{-1} yr^{-1}) under favorable climatic conditions but releases carbon (1.0 MgC ha^{-1} yr^{-1}) to the atmosphere under climatic stress (Fig. 1). The forest sequestered carbon at a similar rate to younger forests at the same latitude during a "la Niña year", but became a source of carbon during a drier, higher temperature year. The average exchange using micrometeorological technologies over a five year period is within the measurement errors of carbon inventory estimates. Observed soil respiration ranged from 8.7 to 11.5 Mg C ha^{-1} yr^{-1} with an average of 10.9 Mg C ha^{-1} yr^{-1}. Water availability is driven by the amount of winter season precipitation and the overall timing of preciptation and especially the end of the rainy season. In years with low overall respiration the stand can act as a strong carbon sink (1999), whereas increased respiratory fluxes in other years can turn the ecosystem into a weak to moderate source.

Hypotheses

The following hypothesis will be tested in this study: Increased length of summer drought will actually increase carbon uptake by the old-growth stand by limiting respiration. The access to deeper soil water and the increased water use efficiency during drought can counter some of the photosynthesis limitations by increased VPD while the drying of the soil surface layer will inhibit microbial activity.

2. METHODS AND MATERIALS

Site description

The WRCCRF (45.821, -121.952) is located in the T.T. Munger Research Natural Area n southern Washington, an old-growth forest ecosystem that is composed primarily of old-growth Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*).

Site instrumentation

The eddy covariance system used at the Wind River Canopy Crane consists of a three dimensional horizontally symmetric sonic anemometer / thermometer (HS Research Anemometer, GILL Instruments, Lymington, UK), a closed path infrared gas analyzer (IRGA) (LI-COR 6262, LI-COR, Lincoln, Nebraska, USA), a Personal Computer (PC) for data logging, and a suite of data acquisition software (RCOM, GILL Instruments, Lymington, Uk before 12/2000 and WINFLUX, SDSU, San Diego, CA, USA after 12/2000), as well as post-processing data analysis package written in FORTRAN 90. The air-sample intake for the IRGA is located 10 cm below the sonic measurement volume, tubing routes the sample air to the IRGA with (flow rate = 10 l/min and sample tube length =5 m).

Ecosystem water-use efficiency (WUE) was estimated for examination of year to year differences which may be explained by interannual variability in water availability. WUE has been defined to be the ratio of carbon dioxide flux to water vapor flux for times when CO_2 is negative (assimilation) and H_2O flux is positive (evaporation and transpiration).

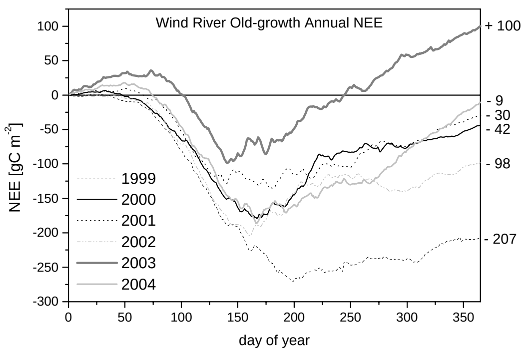

Figure 1: *Seasonal course of cumulative net ecosystem exchange (NEE) for 5 years (1998 – 2004)*

3. RESULTS AND DISCUSSION

Precipitation measurements showed significant interannual variability at the old-growth forest canopy. Annual precipitation varied from a five-year high of 2669 mm in 1999 (a La Niña year) to a low of 1742 mm in the following year. Yearly water availability statistics are found in table 1.

	1999	2001	2002	2003
precip. (mm yr^{-1})	2669	1908	1970	2230
mean Ta (ºC)	9.3	9.1	9.3	10.0
dry season WUE (mg g^{-1})	1.8± 3.2	3.3 ± 8.9	3.4 ± 10.6	3.9 ± 12.1

Table 1: *Total evapotranspiration, water balance, and precipitation, and average air temperature and dry season water-use efficiency by year at the WRCCRF. *ET estimates in 2000 are biased low partially due to water flux data gaps.*

Analysis found that annual net ecosystem exchange (NEE) showed a strong correlation with lagged precipitation for the preceding water year. The water budget year was defined to include the entire rainy season starting in August and ending in July of the next year.

Mean dry-season WUE varied from 1.8 mg g^{-1} in 1999 to 3.9 mg g^{-1} in 2003. WUE in 1999 was significantly lower than any other year ($P < 0.0001$) when the ecosystem experienced little water stress due to excessive winter precipitation and unusually low spring and summer temperatures. Figure 2 shows daily average dry-season WUE values in 1999 and 2001.

Meanwhile we have found evidence that summertime soil respiration is strongly limited by about 40-50% during the drought compared to respiration in the late spring and early summer (Falk et al., 2005). This feature is also evident in overstory NEE measurements shown in Figure 3: While respiration decreases at high temperatures as shown in the right hand panel, A_{max} continues to increase for high temperatures showing the stomatal control on NEE for high air temperature (T_a)that correlate to high Vapor pressure deficit (VPD).

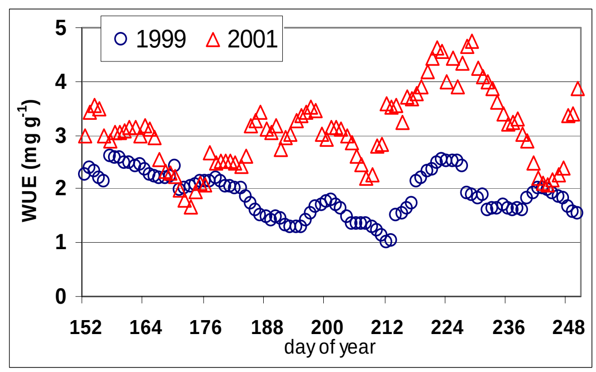

Figure 2: *Dry season WUE varied significantly between 1999 and 2001, indicating that the ecosystem was more efficient at uptaking carbon during the drought-stressed year, than it was when water was plentiful.*

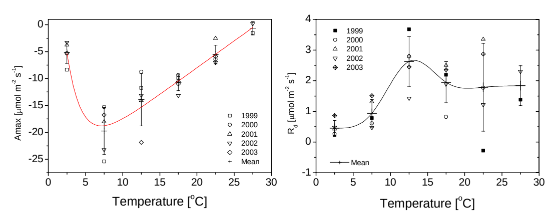

Figure 3: *A_{max} and R_d as a function of T_a for the years 1999 through 2003. Data from all years was averaged and a non-linear fit applied to $A_{max}(T_a)$. While respiration decreases at high temperatures as shown for Rd in the right hand panel, Amax continues to increase for high temperatures showing the stomatal control on NEE for high Ta that correlate to high VPD*

4. CONCLUSION

Due to its maritime climate and low elevation the old-growth forest at the WRCCRF experiences a growing season of 365 days, i.e. assimilation of carbon can occur any day of the year. We find extremely high seasonal and interannual variability depending both on temperature and water availability.

Links between carbon exchange and precipitation suggest that water availability is an important factor in determining whether or not the old-growth forest becomes an annual carbon sink, source, or is at equilibrium. However restrictions on water availability limit respiration and therefore moderate the impact of drought on the annual carbon balance.

Only when several factors such as mild air temperatures, moderate to high radiation levels and an adequate supply of water already stored in the ecosystem converge, carbon sequestration reached its maximum value. Seasonal to interannual variability in precipitation and consequent water balance appears to influence the timing of this switch from photosynthesis-dominance to respiration-dominance, ultimately determining whether the forest will be a net carbon sink or source.

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