Controlling factors of $^{18}O/^{16}O$ isotope ratios of CO_2 respired from four forests on the Oregon Transect

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Introduction

Stable isotopes of oxygen in CO_2 have been used in global models to estimate terrestrial carbon budgets and large-scale carbon fluxes, based on modeled assumptions regarding ecosystem-level isotope respiration. At the global scale, oxygen-18 (^{18}O) has a regular annual fluctuation in the atmosphere, but its behavior is not well understood empirically at the level of the ecosystem. The present study investigates some of the potential factors controlling the oxygen isotope ratio ($\delta^{18}O$) of ecosystem-respired CO_2 and its variability. Precipitation and evaporation are indicated as controllers, and there is evidence of some local variability over time.

Site location and methods

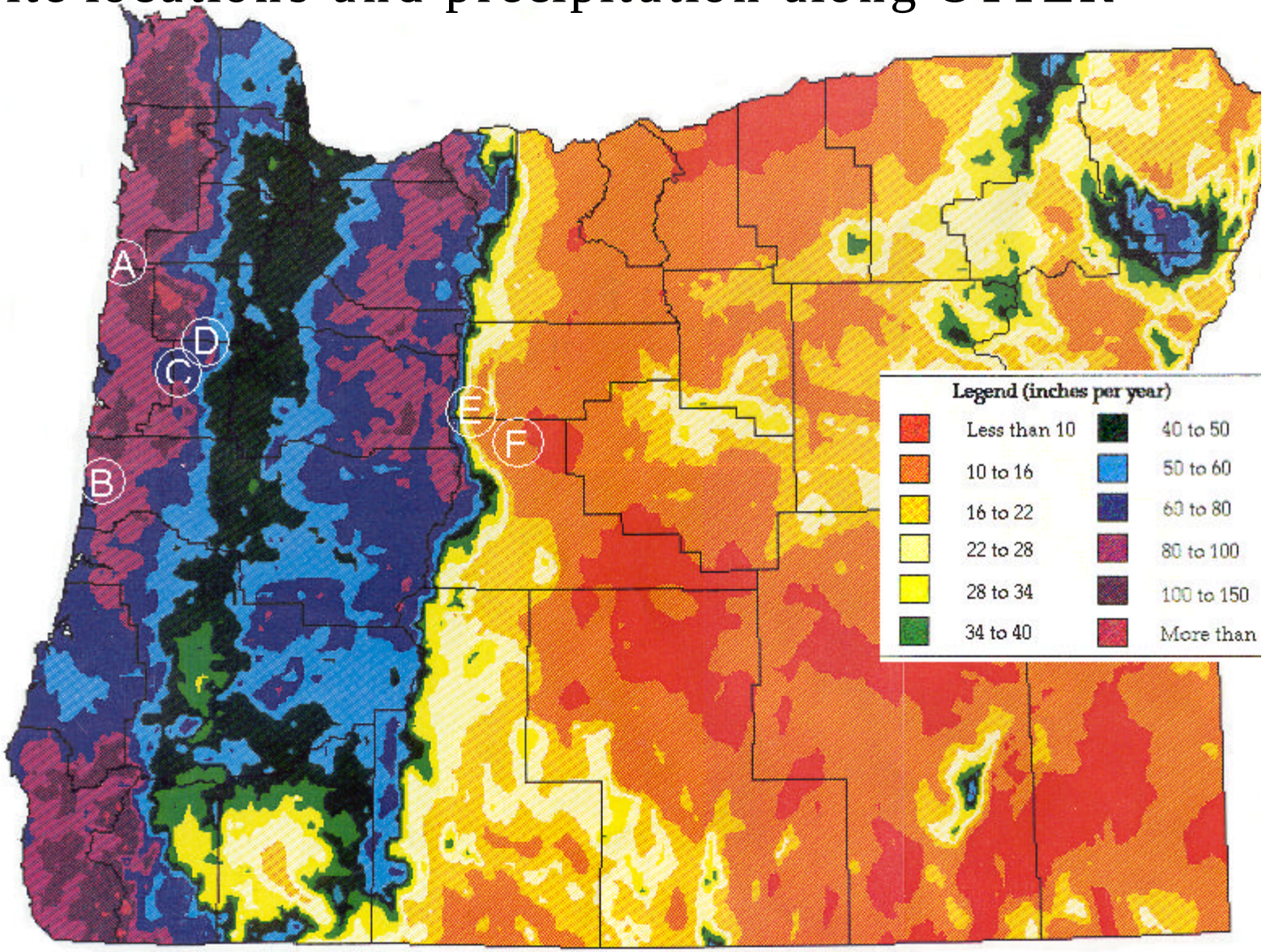
This study makes use of the Oregon Transect for Terrestrial Ecosystem Research (OTTER), a transect of sites in Oregon covering an order-of-magnitude difference in annual precipitation in a distance of 250 km. In addition, the transect can be broken into four vegetation zones characterized by different dominant tree types and representing a gradient of productivity levels. The wide range in precipitation and productivity in a relatively short distance makes the transect ideal for investigation of potential variability among ecosystem types. Sites in each of the four forest zones were used in 1996, 1997, 2000, and 2001. (Fig.1)

The sites were sampled for Keeling plots approximately monthly, in January and May through November 2000, and in the summers of 1996 and 1997. Weather data were obtained from nearby weather stations with the exception of the pine site, where climatic data are collected on-site.

Figure 1. Site locations and precipitation along OTTER

1996/7 sites:
A, D, E, F

2000/1 sites:
B, C, E, F



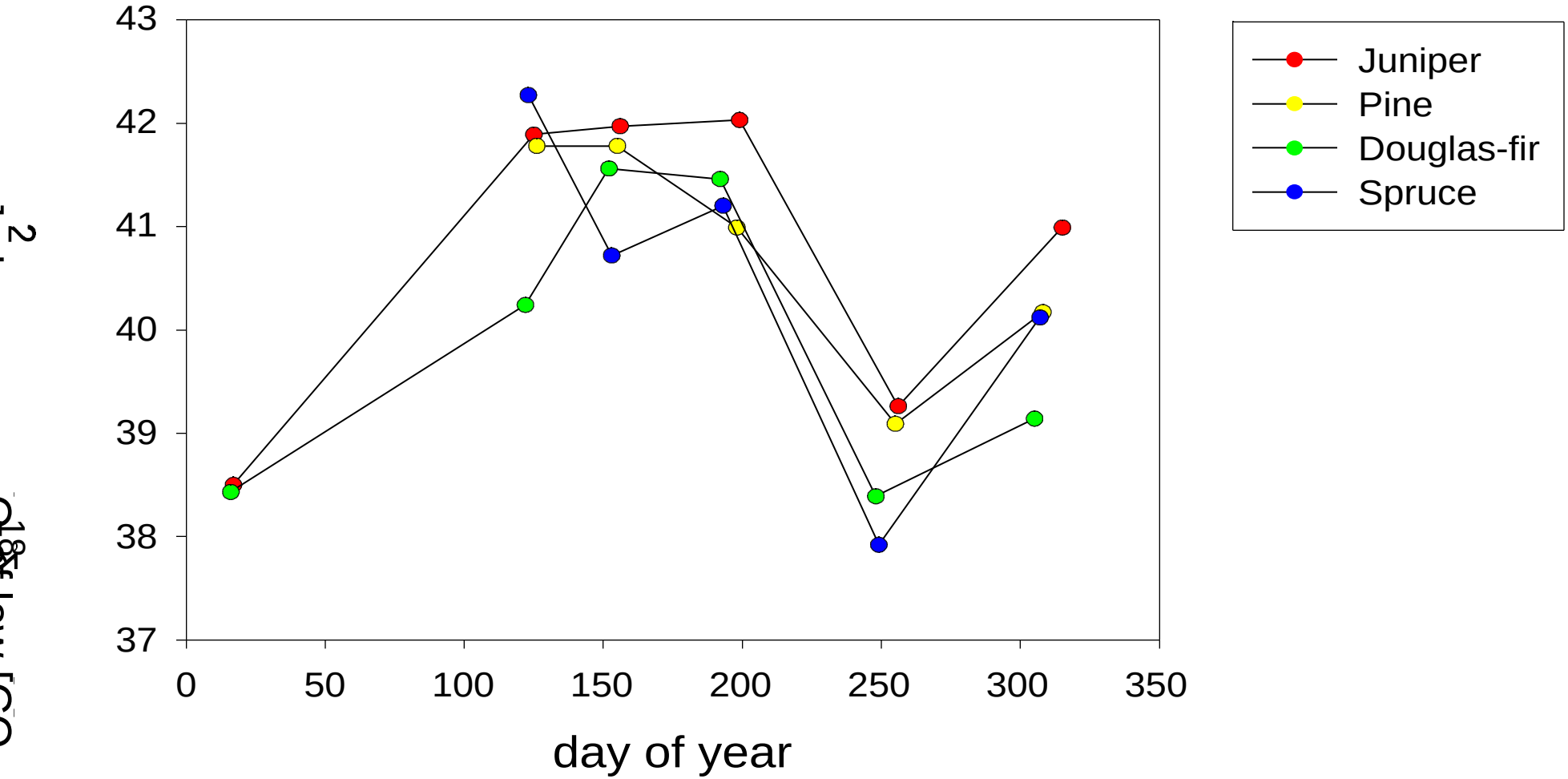
Forest types:
A, B – Sitka spruce
C, D – Douglas-fir/Western hemlock
E – Ponderosa pine
F – Western juniper

Atmospheric ^{18}O

The air within a forest canopy that is lowest in CO_2 is from the upper canopy, represents above-canopy atmospheric air, and is presumed least affected by respiration of local vegetation and soils. Using this approximation yields results which match the seasonal trends found by others who measured the atmosphere more directly. At all four sites in 2000, $\delta^{18}O$ of air at low [CO_2] followed the global trend of a low in winter and peak in early spring. (Fig.2)

This pattern has been attributed to temperature-driven changes in $\delta^{18}O$ of H_2O in precipitation, CO_2-H_2O equilibrium fractionation, and ecosystem respiration rates.

Figure 2. Annual trend in estimated atmospheric $\delta^{18}O$



When CO_2 comes into contact with H_2O, in soil water pools, in plant stomata, or in the ocean, it quickly equilibrates so that the $\delta^{18}O$ value of the CO_2 matches that of the water. Hence the isotope ratio of CO_2 in air follows trends in $\delta^{18}O$ of precipitation through the year. This equilibration process is also temperature-dependent, and acts to reinforce the annual pattern.

In addition, respiration rates are seasonal, driven by temperature and moisture—plants and soils respire more in warm, wet weather. Since $\delta^{18}O$ of CO_2 respired by ecosystems is lower than that of the atmosphere, respiration lowers the $\delta^{18}O$ value of atmospheric air during the spring and summer.

The Keeling Plot

Inside a forest at night, plants and soils respire CO_2 but do not take it up, so that net CO_2 flux is equal to the flux leaving the system. The CO_2 respired by the ecosystem has an isotopic signature, determined by $\delta^{18}O$ of soil and leaf water and temperature-dependent fractionations, and differs from that of atmospheric air.

Air samples are collected throughout the night as $[CO_2]$ rises due to respiration. This increase also drives the isotopic signature of forest canopy air toward that of its respiring components. (Fig.3) The theoretical equilibrium value, where the $\delta^{18}O$ -$[CO_2]$ curve levels off and all CO_2 comes from respiration, is equal to the y-intercept of $[CO_2]^{-1}$ plotted against $\delta^{18}O$. (Fig.4)

Figure 3. $[CO_2]$ vs. $\delta^{18}O$

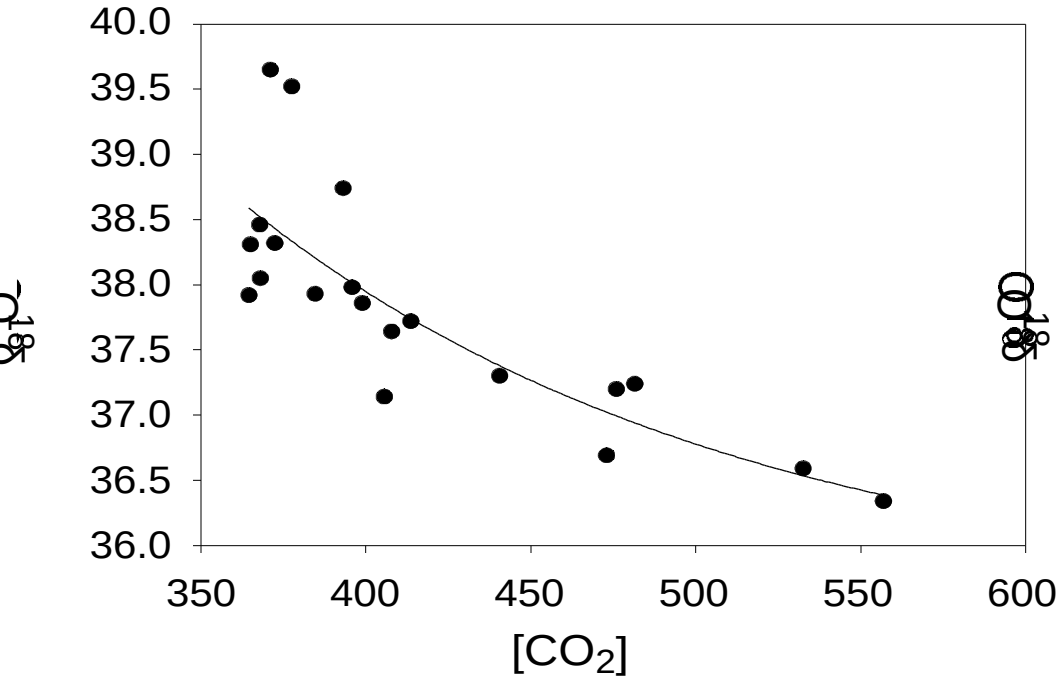
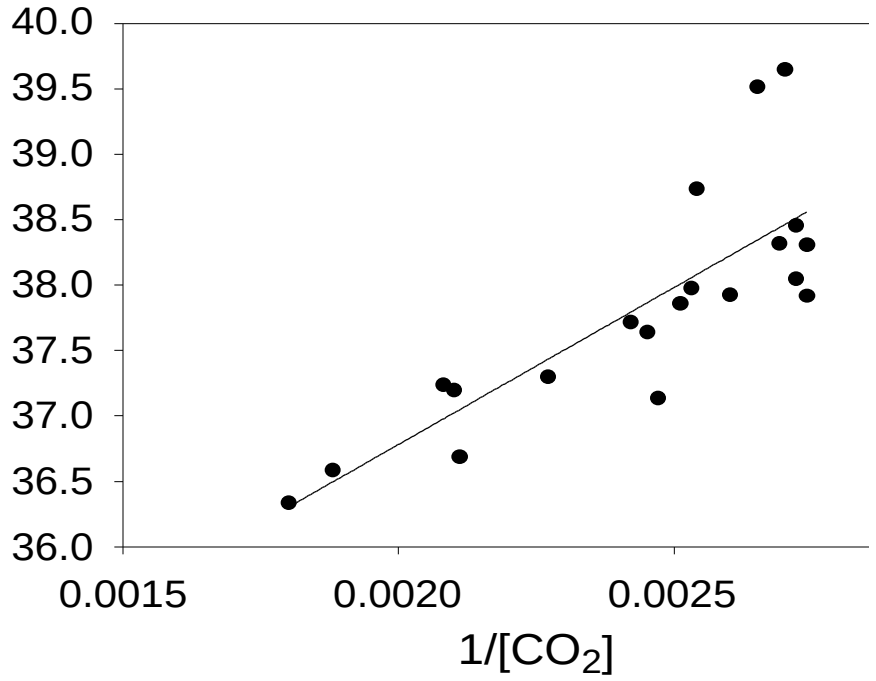


Figure 4. A Keeling plot – $[CO_2]^{-1}$ vs. $\delta^{18}O$



The graph in Figure 4 is known as a Keeling plot, after its inventor, Dr. Charles D. Keeling, and its intercept is a measure of the ecosystem-respired isotope ratio.

However, the Keeling plot method often produces plots with low correlation and y-intercepts with high standard errors.

Figure 5. A Keeling plot with high standard error

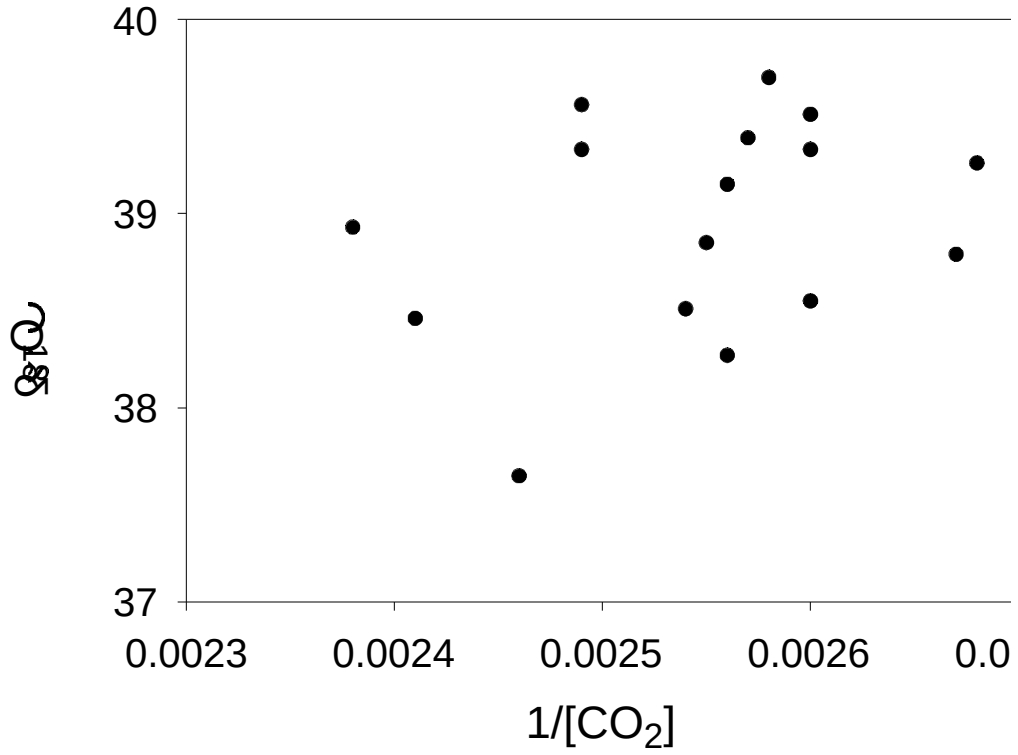


Figure 5 shows a less successful Keeling plot of $\delta^{18}O$. I hypothesized that this variability in the data might be a result of changes in source $\delta^{18}O$ throughout the night.

A review of Keeling plots collected in 1996, 1997, and 2000 was conducted to determine some of the factors influencing precision. Since the end product of a Keeling plot analysis is the y-intercept, standard error of intercept was the precision measure used.

The standard error of the intercept of a $\delta^{18}O$ Keeling plot decreases with increasing $[CO_2]$ range and increases with increasing time between the first and last samples. (Fig.6,7) Hence the ideal Keeling plot would be one for which samples were collected in a short time and covered a large range of $[CO_2]$. This supports the hypothesis that $\delta^{18}O$ of source CO_2 changes during the night; however, the relationship between sampling time range and standard error of intercept is not a close one.

Figure 6. Standard error of Keeling plot intercept vs. [CO_2] range

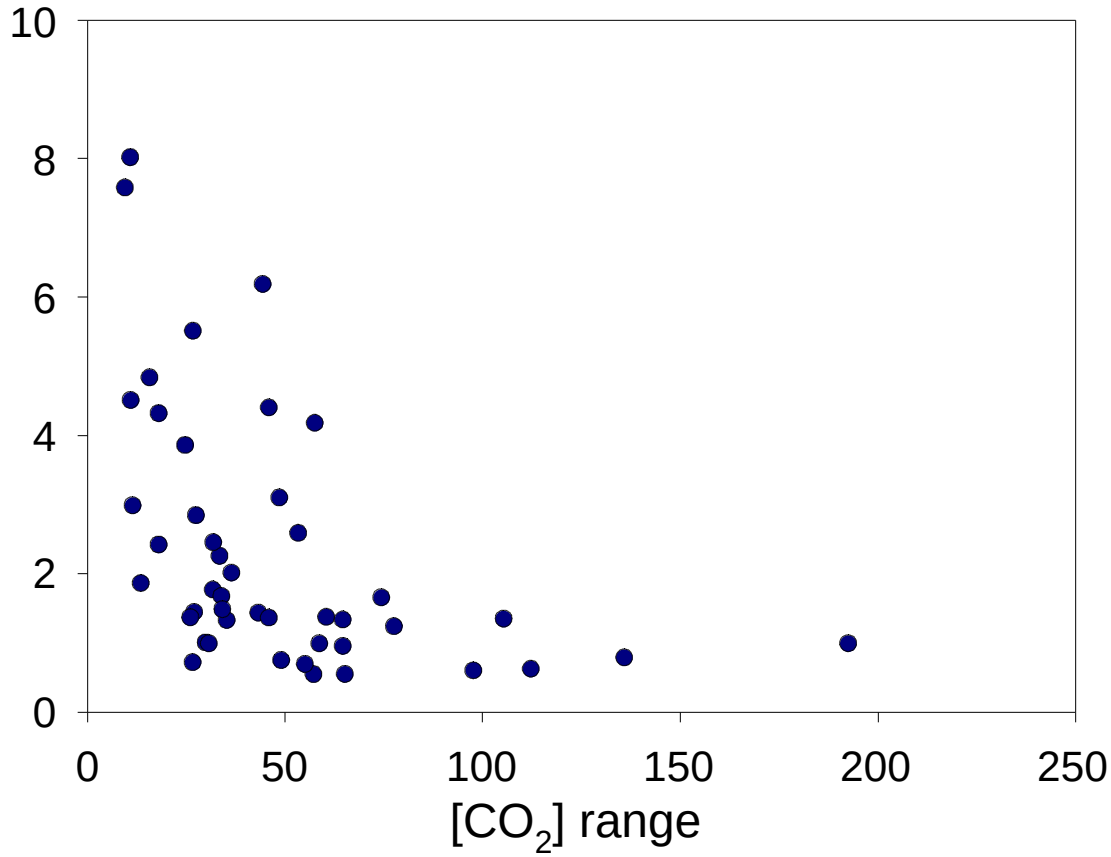
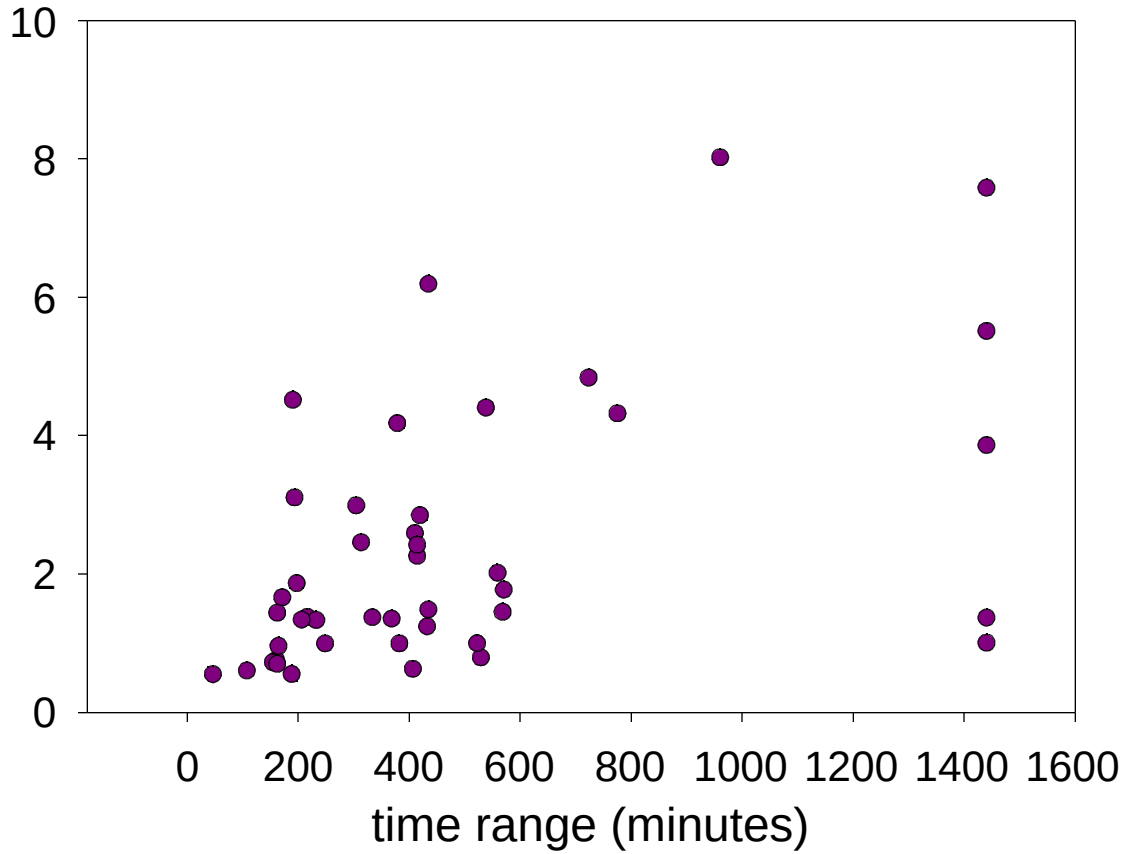


Figure 7. Standard error of Keeling plot intercept vs. sampling time



Vapor pressure deficit

During hot, dry weather, lighter isotopes (such as ^{16}O compared to ^{18}O) preferentially evaporate from soils. I hypothesized that during a precipitation-free interval, respired $\delta^{18}O$ values should increase as evaporation removes ^{16}O, leaving the source soil water enriched in ^{18}O.

The daily average vapor pressure deficit (VPD), a measure of evaporative demand, was summed for each day since the last rainfall for each Keeling plot collected in 2000. At both of the dry sites, ecosystem-respired CO_2 becomes progressively enriched in ^{18}O as evaporation proceeds. At the Douglas-fir site this relationship is less strong, and the spruce site shows no particular trend. (Fig.8) So the hypothesis is supported at the two eastern sites.

Figure 8. Ecosystem-respired $\delta^{18}O$ response to vpd at each

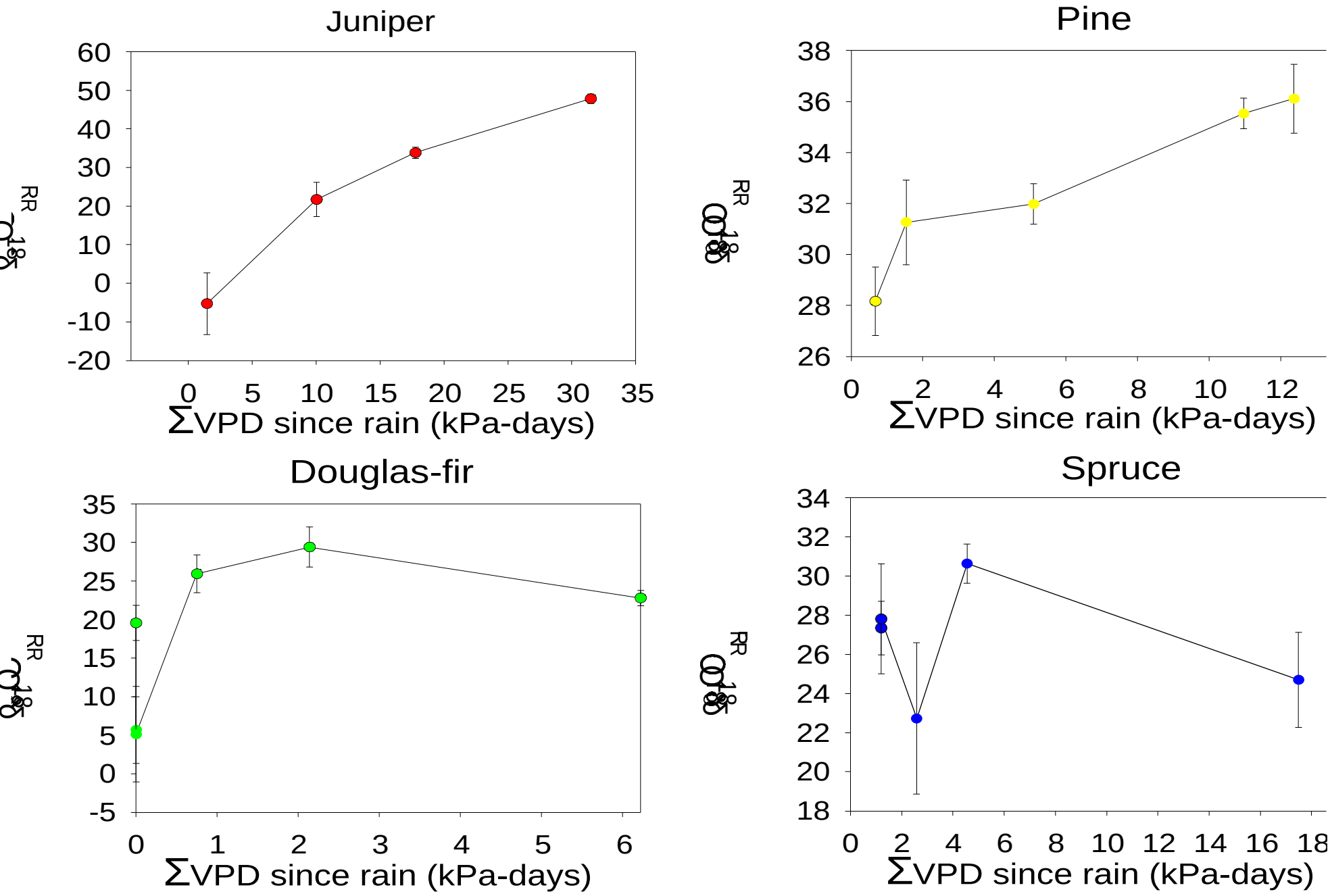
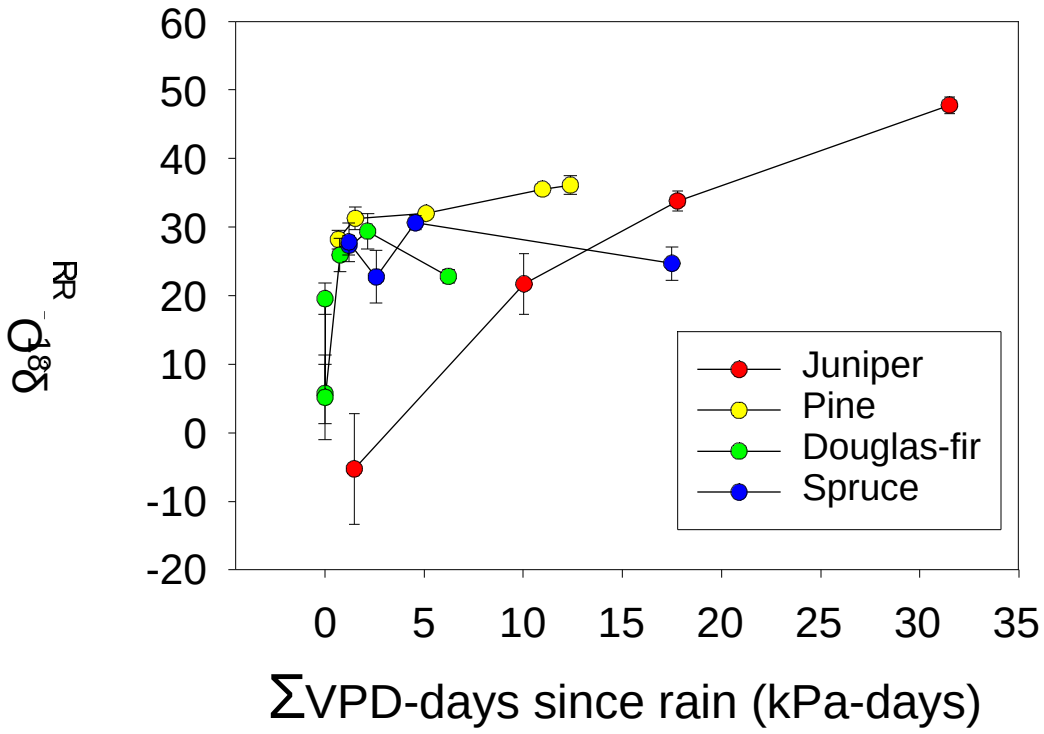


Figure 9. Ecosystem-respired $\delta^{18}O$ response to VPD, all sites

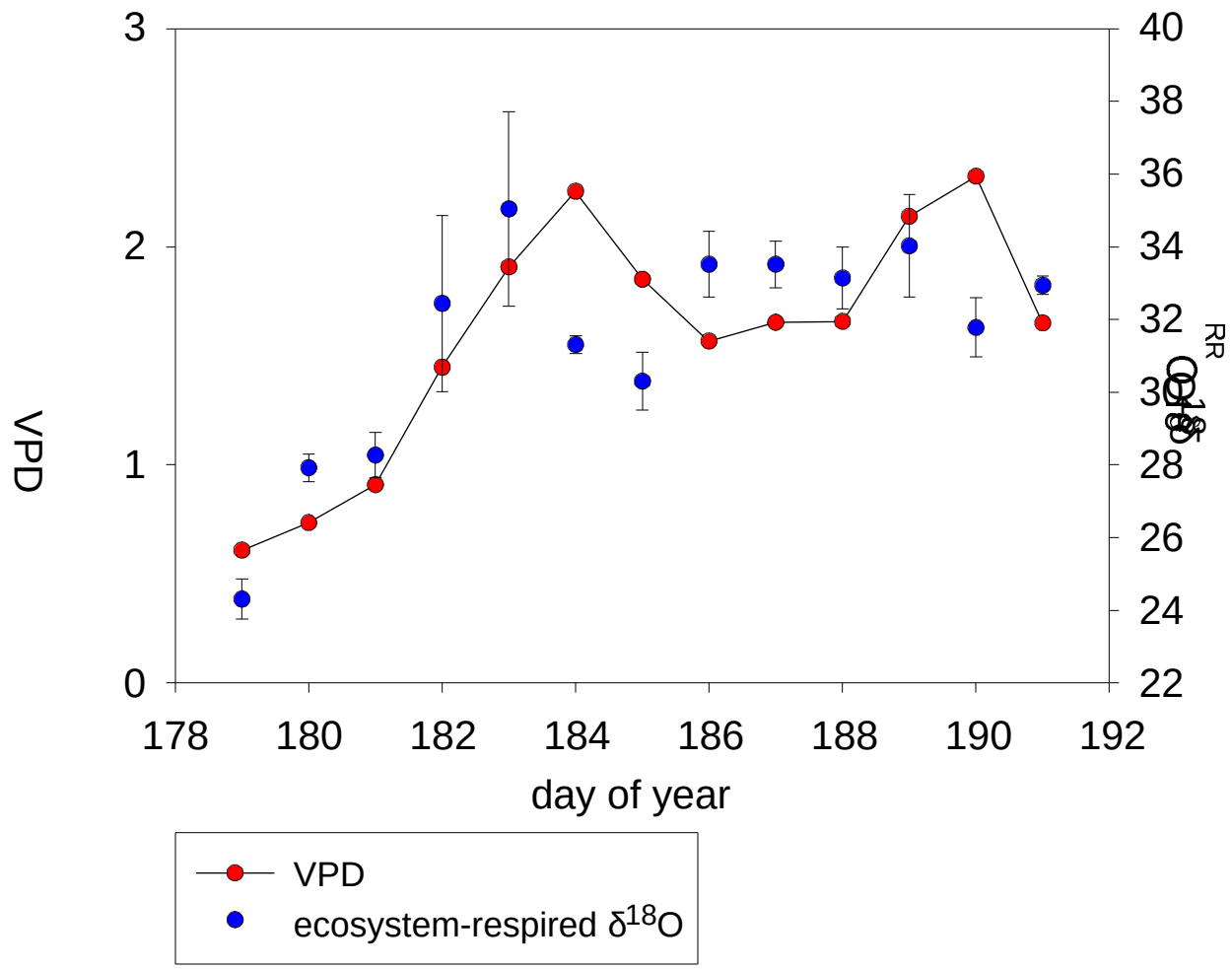


The failure of the two wetter sites to conform to prediction may be caused by the higher level of precipitation and lower level of evaporation there. The driest site, the juniper, experiences a greater range in cumulative VPD than the wet sites. (Fig.9) Rainfall samples collected near the Douglas-fir and juniper sites in 2000 show that the $\delta^{18}O$ of rainwater can change by 10‰ in two days. This variation may be overcome by severe dryness at the eastern sites but not at the western.

In addition, the vegetation component of ecosystem respiration is much higher at the wet sites, while I hypothesize that VPD-driven enrichment in ^{18}O is due to enrichment of the soil-respired CO_2. If plant-respired CO_2 does not respond to VPD as soil-respired CO_2 does, a weaker trend should be expected at the western sites.

In 2001 the hypothesis of VPD-driven enrichment was tested at the finer time scale of a single site, the Ponderosa pine site, sampled on 13 consecutive nights. The first night of sampling followed a day of rain, but the remainder of the sampling period was dry. Figure 10 shows the increase in VPD and corresponding enrichment in respired $\delta^{18}O$ that occurred as expected over the next four days, until $\delta^{18}O$ apparently reached a plateau. The plants at the site where these measurements were made have access to groundwater, so the plateau may be a result of hydraulic redistribution by tree roots in response to decreasing soil moisture.

Figure 10. $\delta^{18}O$ and VPD at the Ponderosa Pine site, summer 2001



Conclusions

At the ecosystem level, the $\delta^{18}O$ signature of air in the upper canopy follows an annual trend similar to that recorded for the free atmosphere. $\delta^{18}O$ of forest canopy respiration may vary over time within a single night, suggesting a possible change in source isotope ratio.

Cumulative VPD over a precipitation-free period is a predictor of ^{18}O enrichment of respired CO_2 at the pine and juniper sites. This evaporative enrichment is not apparent at the Douglas-fir and spruce sites, possibly due to masking of the effect by variation in precipitation $H_2{}^{18}O$ and a high vegetation-derived component of respiration.

Acknowledgments

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