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^{13}C content of ecosystem respiration is linked to precipitation and vapor pressure deficit

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Abstract Variation in the carbon isotopic composition of ecosystem respiration ($\delta^{13}\text{C}_R$) was studied for 3 years along a precipitation gradient in western Oregon, USA, using the Keeling plot approach. Study sites included six coniferous forests, dominated by *Picea sitchensis*, *Tsuga heterophylla*, *Pseudotsuga menziesii*, *Pinus ponderosa*, and *Juniperus occidentalis*, and ranged in location from the Pacific coast to the eastern side of the Cascade Mountains (a 250-km transect). Mean annual precipitation across these sites ranged from 227 to 2,760 mm. Overall $\delta^{13}\text{C}_R$ varied from -23.1 to -33.1‰ , and within a single forest, it varied in magnitude by 3.5–8.5‰. Mean annual $\delta^{13}\text{C}_R$ differed significantly in the forests and was strongly correlated with mean annual precipitation. The carbon isotope ratio of carbon stocks (leaves, fine roots, litter, and soil organic matter) varied similarly with mean precipitation (more positive at the drier sites). There was a strong link between $\delta^{13}\text{C}_R$ and the vapor saturation deficit of air (*vpd*) 5–10 days earlier, both across and within sites. This relationship is consistent with stomatal regulation of gas exchange and associated changes in photosynthetic carbon isotope discrimination. Recent freeze events caused significant deviation from the $\delta^{13}\text{C}_R$ versus *vpd* relationship, resulting in higher than expected $\delta^{13}\text{C}_R$ values.

Keywords Coniferous forest · Isotope · Oregon transect · OTTER · Precipitation transect

Introduction

Two important parameters in the mass balance equations (e.g., Tans et al. 1993; Fung et al. 1997) that are used to assess the magnitude of the terrestrial carbon sink are photosynthetic discrimination (Δ) and the carbon isotopic composition of ecosystem respiration ($\delta^{13}\text{C}_R$). These are generally averaged or modeled over some temporal and spatial scale that corresponds to observations. (Δ and $\delta^{13}\text{C}_R$ correspond to ϵ_{iph} and δ_{ib} , respectively, in Tans et al. 1993, and to Δ and δ_{b} , respectively, in Fung et al. 1997). The extent to which Δ and $\delta^{13}\text{C}_R$ vary could potentially alter conclusions about the timing and nature of the terrestrial carbon sink (J.T. Randerson, personal communication). At present, we only marginally understand the magnitude of spatial and temporal variation in $\delta^{13}\text{C}_R$, and we know very little about how environmental factors might influence ecosystem-level Δ and $\delta^{13}\text{C}_R$ and the extent to which these parameters might be linked.

Many studies in the last decade have examined the carbon isotopic composition of CO_2 respired by terrestrial ecosystems using the two-component gas-mixing model introduced by Keeling (1958; see studies listed in Buchmann et al. 1998). Keeling's theory predicts that the integrated carbon isotope ratio of CO_2 produced by all respiring components of an ecosystem can be determined as the intercept of a regression of $\delta^{13}\text{C}$ versus $1/[\text{CO}_2]$ ($[\text{CO}_2]$ denotes mole fraction of CO_2), where both quantities are measured on air collected in the ecosystem at night. Nocturnal sampling avoids the possible complications of photosynthesis on the respiration signal.

Modeling studies indicate that large-scale isotope discrimination by photosynthesis in the terrestrial biosphere can vary dramatically (Lloyd and Farquhar 1994; Fung et al. 1997). Large variation in measured $\delta^{13}\text{C}_R$ has been reported across biomes, usually representing only a single point in time. While the difference between C_3 - and C_4 -dominated biomes provides the largest observed variation in $\delta^{13}\text{C}_R$ (Still 2000), there can be substantial (more than 10‰) variation in $\delta^{13}\text{C}_R$ within pure C_3 ecosystems (e.g., Buchmann et al. 1997b).

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Relatively few studies have addressed the variability in $\delta^{13}\text{C}_R$ over time. Flanagan et al. (1996, 1999) examined changes in $\delta^{13}\text{C}_R$ in coniferous (*Picea*, *Pinus*) and deciduous (*Populus*) forests in Canada, and found little variation within a season except at their southernmost *Populus* site. Buchmann et al. (1997a) reported no difference in the isotopic signature of ecosystem respiration in a tropical forest in French Guiana in wet versus dry seasons. In contrast, Buchmann et al. (1997b) found marked variation in $\delta^{13}\text{C}_R$ in several Utah (USA) forests, including boxelder (*Acer*), aspen (*Populus*), and pine (*Pinus*). Because environmental stresses such as drought or cold alter CO_2 assimilation rate, stomatal conductance, and photosynthetic discrimination in predictable ways (Farquhar et al. 1989), there could be important changes in Δ in terrestrial ecosystems that are reflected in $\delta^{13}\text{C}_R$ when the assimilated carbon is respired. Recent studies have shown a direct and rather rapid link between photosynthetic assimilation, soil respiration rate, and ^{13}C in respired CO_2 (Ekblad and Högberg 2001; Högberg et al. 2001).

The aim of this study was to investigate the factors influencing variability in the isotopic composition of ecosystem respiration ($\delta^{13}\text{C}_R$). The degree to which $\delta^{13}\text{C}_R$ might vary at forested sites with widely differing water availability was examined at several sites across a precipitation gradient in western Oregon, USA, where precipitation varies quite strongly both spatially and seasonally (Peterson and Waring 1994).

We hypothesized that sites with higher precipitation would have more negative carbon isotope ratios in plant and soil organic matter, and that respired CO_2 signatures ($\delta^{13}\text{C}_R$) would therefore follow the same pattern. As water availability decreases, physiological adjustments by plants should change in response to soil and plant water status, affecting hydraulic and stomatal conductance, and thus photosynthetic discrimination (Ehleringer 1994; Ehleringer and Cerling 1995). Presumably, some portion of the CO_2 respired by an ecosystem must be composed of recently fixed carbon. Since a significant proportion of total ecosystem respiration may originate through heterotrophic decomposition of recalcitrant soil organic matter, the degree to which changes in Δ might be reflected in $\delta^{13}\text{C}_R$ is less clear. This study was designed to illuminate these issues.

Materials and methods

Study sites

This research was conducted along the Oregon transect (Peterson and Waring 1994), which is located in western Oregon, USA (Fig. 1). The transect is among the largest precipitation gradients in the world, with mean annual precipitation varying by nearly 3,000 mm within 250 km. This region is characterized by wet winters and dry summers. It is dominated by long-lived conifers (Waring and Franklin 1979), and vegetation patterns are linked to precipitation patterns (Fig. 1). Six coniferous forests were selected (Table 1); dominant species in the forests included *Picea sitchensis*

Fig. 1 Location of study sites shown on a map of major vegetation zones in western Oregon. Arrows at the top indicate the mean annual precipitation at each study site. The inset figure shows the strong seasonal pattern in mean monthly precipitation at each site. Adapted from Franklin and Dyrness (1988), and Taylor and Hannan (1999)

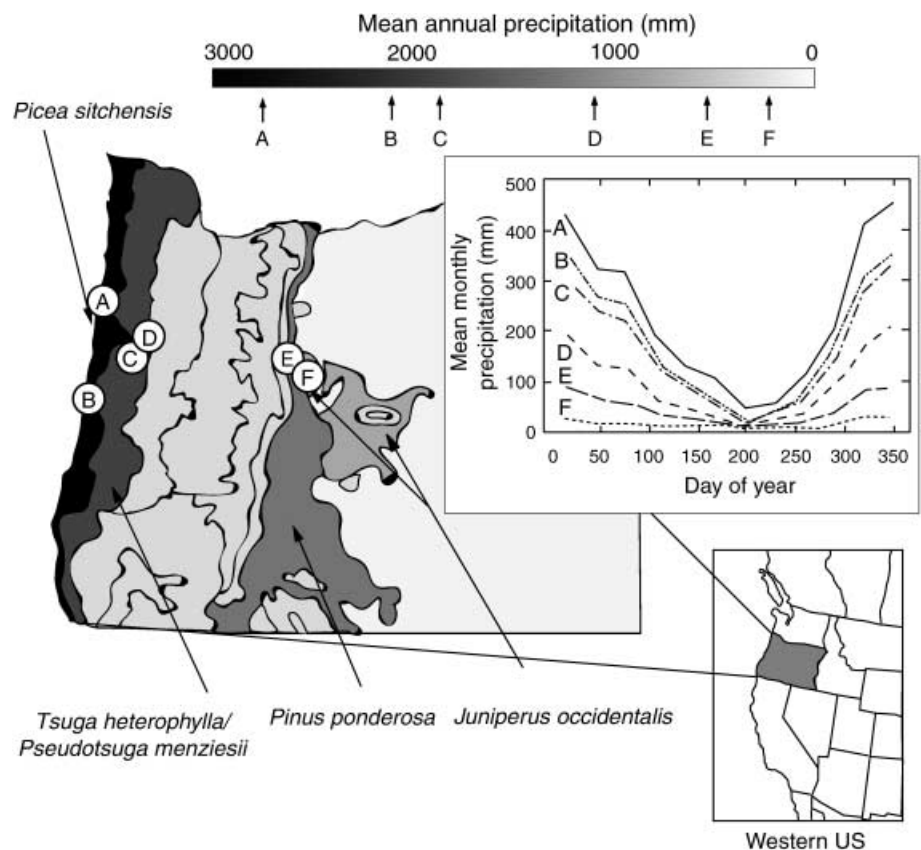


Table 1 Relevant site details, with sites arranged in order from wettest site to driest. Sites and site codes are unique to this project and do not correspond to sites on the original Oregon transect, ex-

cept for A (Cascade Head, originally site 10). Climate station names are consistent with Taylor and Hannan (1999) (*vpd* vapor saturation deficit of air)

Site code	Dominant species	Location and elevation	Approximate stand age (years)	Canopy height (m)	PRISM modeled 30-year mean precipitation (mm)	Nearest distance station with measured 30-year mean precipitation (mm) and from site	Nearest <i>vpd</i> station (km)	Years sampled	Site reference ^a
A	<i>Picea sitchensis</i> , <i>Tsuga heterophylla</i>	45°03' N, 123°57' W, 240 m	150	50	2,760	2,470 (Otis 2 NE, 4 km)	None	1996, 1997	Gholz (1982), Harcombe et al. (1990), Peterson and Waring (1994)
B	<i>P. sitchensis</i> , <i>T. heterophylla</i>	44°07' N, 124°07' W, 300 m	30	11	2,129	1,930 (Honeyman State Park, 13 km)	None	2000	None
C	<i>Pseudotsuga menziesii</i>	44°35' N, 123°35' W, 290 m	15	8	1,892	1,680 (Corvallis Water Bureau, 10 km)	Corvallis (18)	2000	None
D	<i>P. menziesii</i>	44°36' N, 123°16' W, 310 m	30	23	1,140	1,084 (Corvallis, 9 km)	Corvallis (9)	1996, 1997	Bond and Kavanaugh (1999)
E	<i>Pinus ponderosa</i>	44°30' N, 121°37' W, 941 m	45/250 ^b	9/33 ^b	523	602 (on site ^c)	On site	1996, 1997, 2000	Anthoni et al. (1999), Law et al. (1999a, 1999b)
F	<i>Juniperus occidentalis</i>	44°18' N, 121°20' W, 930 m	75/230 ^b	4/10 ^b	227	217 (Redmond, 12 km)	Redmond (12)	1996, 1997, 2000	Gholz (1982), Miller et al. (1992)

^a Site E is an AmeriFlux long-term CO₂ flux study site (Metolius Research Natural Area), and site F is near (but not identical to) the sites used by Gholz (1982) and Miller et al. (1992)

^b Sites E and F have two age and height classes

^c Measured precipitation at site E is the mean of 1996–2000

sis and *Tsuga heterophylla* (mixed Sitka spruce and western hemlock, two sites), *Pseudotsuga menziesii* (Douglas fir, two sites), *Pinus ponderosa* (ponderosa pine, one site), and *Juniperus occidentalis* (western juniper, one site). The sites differed in age and canopy structure, but only minimally in elevation. Two original sites (A and D) were inaccessible in 2000, and were replaced with nearby conspecific stands (B and C). We anticipated a strong environmental gradient effect on $\delta^{13}C_R$, and preliminary results at site A did not follow our expectations (Ehleringer and Cook 1998). Previous studies have shown that this particular stand is characterized by unusually low productivity (Runyon et al. 1994). We hypothesized that stand age might be important in determining $\delta^{13}C_R$, and therefore selected a younger stand to replace site A in 2000 (Table 1). The *P. ponderosa* site (E) is a long-term CO₂ flux-monitoring site (Metolius Research Natural Area) in the AmeriFlux network and has been studied extensively (Anthoni et al. 1999; Law et al. 1999a, 1999b, 2000). Further site details are available in Table 1 and references therein.

Measurements were conducted during 1996, 1997, and 2000. Annual precipitation during these years was 151, 95, and 86% of normal, averaged across all our sites.

Air sampling

Air samples were collected at night from a variety of heights within the canopy, depending on the forest. In total, 1,068 air samples

were collected during 45 different time periods. Air samples were chemically dried with magnesium perchlorate during collection and saved in 100-ml glass flasks with Teflon stopcocks (34-5671; Kontes Glass Co., Vineland, N.J.). CO₂ mole fraction was measured in the field using a portable photosynthesis system (LI-6200; LI-COR, Inc., Lincoln, Neb.) during all sampling periods, and additionally in the laboratory using the method of Bowling et al. (2001a) during 2000. Based on the comparison of the two methods during 2000, we estimate the accuracy of the field measurements at 1.0 ppm, and of the laboratory measurements (year 2000 samples), 0.3 ppm.

Carbon isotope ratios of CO₂ in the flasks were measured on a continuous-flow isotope ratio mass spectrometer (IRMS; Finnigan MAT 252 or DELTAplus, San Jose, Calif.), as described by Ehleringer and Cook (1998). Precision for $\delta^{13}C$ was determined daily by comparison to known standards and was typically $\pm 0.1\%$. Corrections for the presence of ¹⁷O were applied, and CO₂ was separated from N₂O by gas chromatography before analysis. We report all carbon isotope ratio values in this paper relative to the international PDB standard.

$\delta^{13}C_R$ was evaluated using the Keeling plot approach (Keeling 1958). We used geometric mean (GM) regressions on nocturnal data only, and report our uncertainties as the standard error of the intercept (Sokal and Rohlf 1995). Outliers were selected and removed (if necessary) on each Keeling plot based on a modification of the method of Lancaster (1990). This consisted of (1) performing a GM regression with all data points on the plot, (2) removing

any points where the absolute value of the residual was greater than 2 standard deviations (SDs) of all the absolute residuals, (3) recalculating the GM regression with the remaining points, and (4) repeating steps 2 and 3 until all residuals were within 2 SD. This resulted in the removal of 64 individual air samples from analysis (6.0% of the total).

Organic samples

The carbon isotopic composition of leaves, fine roots, litter, and bulk soil organic matter was monitored during 2000 at sites B, C, E, and F. Sun and shade needles were collected during each site visit in 2000 (five time periods, three replicates each). In January 2000, three soil pits were excavated at each site, and samples collected in 5-cm depth increments to a maximum depth of 25 cm. Litter was separated into fresh and old (largely decomposed but still recognizable as needles) categories. All organic samples were dried at 60°C to constant mass. Roots were removed from the soil samples and fine roots (<2 mm diameter) saved. Root-free soil samples were acid-washed (0.5 N HCl) to remove carbonates; roots were not treated with acid. Leaves, litter, roots, and bulk soil were ground to No. 20 mesh and 2- to 20-mg samples were combusted and analyzed for $\delta^{13}\text{C}$ on an IRMS (deltaS; Finnigan MAT). Measurement precision for the organic samples was 0.2‰, and data are presented as means and standard errors (SEs).

Weather and climate data

Weather and climate data at each site were provided by the Oregon Climate Service (OCS) at Oregon State University (<http://www.ocs.orst.edu/>). Site E is fully instrumented and on-site data were used whenever possible (details in Anthoni et al. 1999). We selected existing OCS climate stations as near to the field sites as possible (Table 1), but the climate stations and field sites in many cases differed in altitude. To better estimate precipitation at each site, we used the PRISM model (Daly et al. 1994, 1997), which interpolates between climate stations in mountainous terrain on a 0.040° grid. A comparison of PRISM estimates of 30-year mean annual precipitation with 30-year mean measurements at the nearest climate stations is shown in Table 1. We report our results relative to the 30-year mean PRISM estimates for each site. Air temperature and relative humidity data were also supplied by OCS and used to calculate the water vapor saturation deficit of air (which we refer to in this paper as vapor pressure deficit, or *vpd*). Not all OCS climate stations monitor these parameters, so in some cases, the distance to the *vpd* stations was larger than the distance to the precipitation stations (Table 1). No stations could be identified within the existing OCS network that provided representative air temperature and *vpd* data for our coastal sites (A and B), and thus we were forced to omit the coastal sites from some analyses. For some analyses, we used daytime mean values for *vpd*, and nocturnal mean or minimum values for air temperature. For these purposes, daytime was defined by the hours representing 90% of the half daylength on either side of solar noon (Campbell and Norman 1998), and night hours were defined as midnight to 4:00 a.m.

Ancillary environmental data

Leaf predawn water potential was measured at sites B, C, E, and F during 2000 using a pressure chamber (PMS, Corvallis, Ore.). Soil water potential was estimated by correcting leaf water potentials for sampling height (0.01 MPa m⁻¹). Between four and ten replicates were measured at each site during each of five sampling periods throughout the year. Soil water content was monitored continuously at the *P. ponderosa* site (E) (details in Anthoni et al. 1999), and gravimetric soil water content in soil cores (5 cm diameter, 0–20 cm depth) was determined during two visits at each of the year 2000 sites.

Correlations between $\delta^{13}\text{C}_R$ and environmental variables

We investigated the possibility of a correlation between environmental variables and the carbon isotopic composition of respired CO₂. The environmental variables included factors expected to influence photosynthetic discrimination over a season or between years (precipitation, soil moisture, predawn leaf water potential), and other factors that might influence $\delta^{13}\text{C}_R$ more rapidly, such as air temperature or *vpd* (the latter possibly through changes in photosynthetic discrimination).

Since there is likely to be a delay between the time that carbon is fixed photosynthetically and the time it is respired by various ecosystem components, we examined correlations between $\delta^{13}\text{C}_R$ and *vpd* by examining *vpd* over varying time periods. We (1) calculated averages of daytime *vpd* for time periods varying between 1 and 5 days, and (2) shifted these averages back in time by 0–20 days (a subset of these data are reported here). In this fashion, we could examine how meteorological events lasting for 1, 2, or more days might affect $\delta^{13}\text{C}_R$ respired at some future time period (a lagged response). If on average *n* days were required for recently fixed carbon to serve as a substrate for respiration, then there should be a peak in the correlation coefficient between $\delta^{13}\text{C}_R$ and *vpd* *n* days earlier, provided *vpd* events affect photosynthetic discrimination. For example, a 2-day average and a 4-day shift associated with air sampling performed on Friday night would correspond to the average daytime *vpd* on the preceding Sunday and Monday. A 1-day average and a 0-day shift would correspond to the average daytime *vpd* on the day prior to the night of sampling. Based on initial analyses, periods that included recent freeze events (defined here as air temperatures <0.2°C within the last 7 days) were excluded from the *vpd* regression analysis.

Conductance calculations

To test whether the observed variation in $\delta^{13}\text{C}_R$ was consistent with stomatal induced changes in photosynthetic discrimination, we evaluated whether realistic canopy stomatal conductance values could be obtained from $\delta^{13}\text{C}_R$. First, we assumed $\delta^{13}\text{C}$ of the ambient CO₂ in each forest was –8‰. This assumption may fail in closed canopies (sites A–D in our case) as substantial vertical gradients in $\delta^{13}\text{C}$ exist at some times of the day (Buchmann et al. 1997b). However, the majority of photosynthesis occurs in the well-lit upper portions of the canopy, and flux-weighted averages of $\delta^{13}\text{C}$ near the canopy top can be quite close to –8‰ (Bowling et al. 2001b). Next, we used $c_i/c_a = (\delta^{13}\text{C}_R - (-8) + a)/(b - a)$ (Farquhar et al. 1982) to estimate an integrated c_i/c_a for the forest, where $a = 4.4‰$ and $b = 27‰$ represent the standard fractionations associated with C₃ photosynthesis, and c_i/c_a represents the ratio of intercellular to ambient CO₂. Assuming $c_a = 360 \mu\text{mol mol}^{-1}$, we obtained c_i . Then, using $A-c_i$ curves from the literature (*J. osteosperma*: Ehleringer et al. 1986) or from our own unpublished studies (*P. menziesii*, *P. ponderosa*), we estimated total conductance (stomatal and leaf boundary-layer) to CO₂ using the graphical approach of Farquhar and Sharkey (1982).

Results

Carbon isotopic composition of respired CO₂

Considerable variability was observed in $\delta^{13}\text{C}_R$ within and across sites (Fig. 2). Overall, $\delta^{13}\text{C}_R$ varied from –23.1 (*J. occidentalis*) to –33.1‰ (*P. menziesii*, site D), and within a single forest varied as little as 3.5‰ (*P. ponderosa*) to as much as 8.5‰ (*P. menziesii*, site D). There was a correlation ($r^2 = 0.52$, $P = 0.11$, $n = 6$) between the mean of all Keeling plot intercepts within a particular forest (mean $\delta^{13}\text{C}_R$) and the mean annual precipitation at that site

Table 2 Results of linear regressions of $\delta^{13}\text{C}_R$ versus (1) precipitation during the month preceding sampling, (2) mean nocturnal (midnight–4:00 a.m.) air temperature, (3) leaf predawn water potential, and (4) soil water content. Asterisks indicate levels of significance of the regression coefficient (* $P<0.05$, ** $P<0.01$, *** $P<0.001$, Student's t -distribution). A dash indicates data not available

Site	Precipitation previous month		Nocturnal air temperature		Leaf predawn water potential		Soil water content	
	r^2	n	r^2	n	r^2	n	r^2	n
All sites	0.256***	45	0.014	31	0.364**	18	0.313*	17
<i>Picea-Tsuga</i> (A)	0.113	7	–	–	–	–	–	–
<i>Picea-Tsuga</i> (B)	0.295	5	–	–	0.839	4	–	–
<i>P. menziesii</i> (C)	0.954**	5	0.618	5	0.664	5	–	–
<i>P. menziesii</i> (D)	0.001	6	0.133	5	–	–	–	–
<i>P. ponderosa</i> (E)	0.001	11	0.001	11	0.015	5	0.067	11
<i>J. occidentalis</i> (F)	0.006	11	0.004	10	0.007	4	–	–

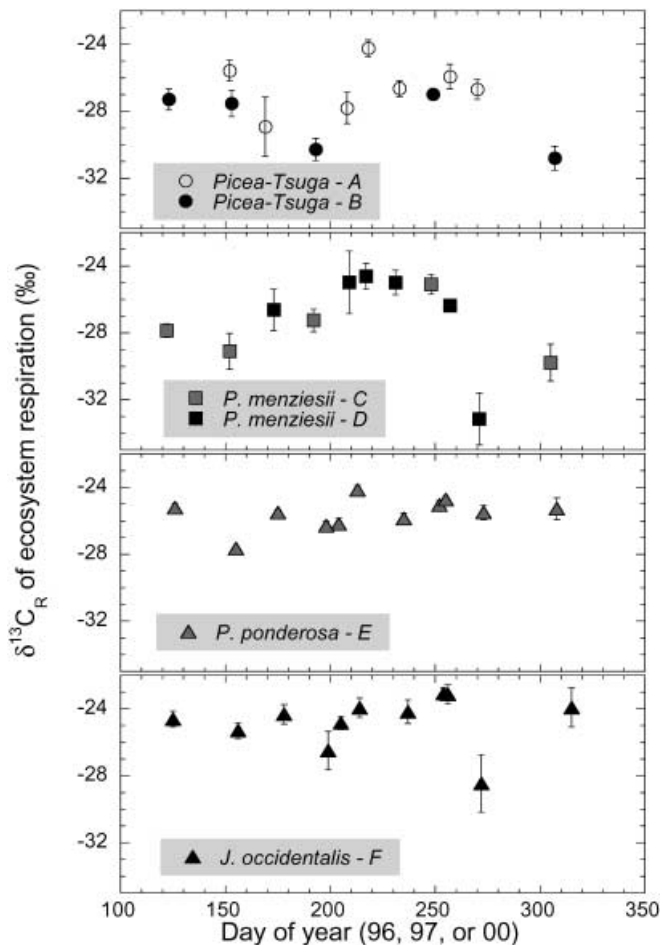


Fig. 2 Carbon isotopic composition of ecosystem respiration (Keeling plot intercept) versus day of year, from six forests in three different years (1996, 1997, and 2000). Sites are arranged top to bottom in order of decreasing annual precipitation

(Fig. 3a), regardless of whether the PRISM estimates or nearby OCS station precipitation measurements were used (Table 1). This correlation was considerably stronger and highly significant when the wettest site (*Picea-Tsuga*, site A) was excluded ($r^2=0.99$, $P<0.01$, $n=5$). In general, $\delta^{13}\text{C}_R$ was more negative at the wettest sites. Although the sites do differ somewhat in altitude (Table 1), the range in altitude is likely not great enough to cause major changes in discrimination (Marshall and Zhang 1994).

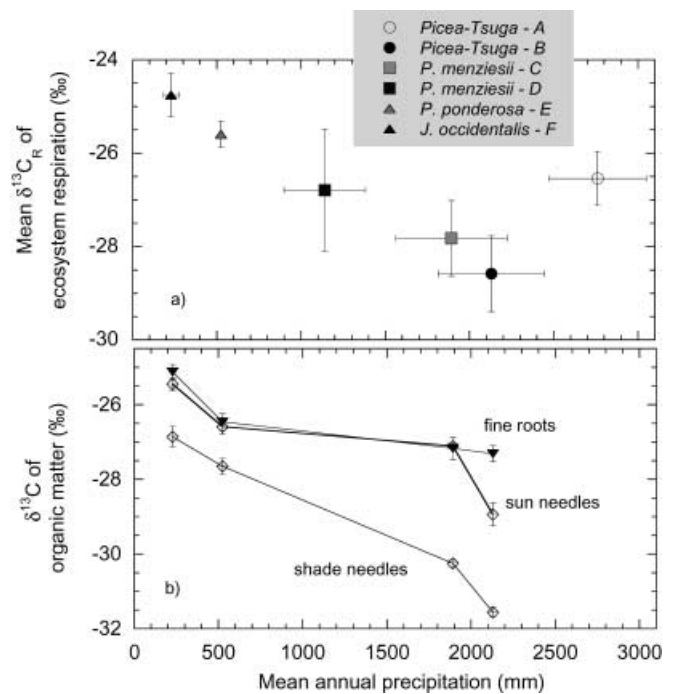


Fig. 3 a $\delta^{13}\text{C}_R$ of ecosystem respiration (means \pm 1 SE) versus mean annual precipitation (means \pm 1 SD) for the six forests. **b** $\delta^{13}\text{C}$ (means \pm 1 SE, $n=15$) of sun leaves, shade leaves, and fine roots, collected at the year 2000 study sites. Error bars are smaller than the symbols in some cases

Correlations with other environmental and biological variables likely to influence plant water relations were generally weak (Table 2). Significant correlations were observed between $\delta^{13}\text{C}_R$ and (1) the precipitation in the month preceding air sampling, (2) leaf predawn water potential on the night of sampling, and (3) concurrent soil water content, but only when all sites were considered together. Considering data within a single site only, one site (*P. menziesii*, site C) showed a significant correlation with precipitation of the preceding month. All other correlations were non-significant (Table 2).

Leaf, litter, and soil organic matter

The pattern of wetter sites having more negative isotope ratios was also observed in leaf tissue and in fine roots

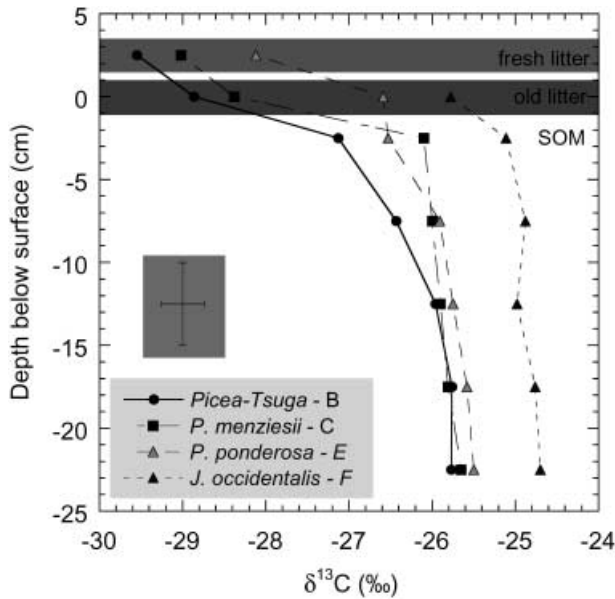


Fig. 4 Mean $\delta^{13}\text{C}$ of forest litter and bulk soil organic matter (SOM) profiles, in 5-cm depth increments (0–5, 5–10 cm, etc.), for the year 2000 study sites. A typical error bar (5-cm depth range, and $\delta^{13}\text{C}$ values ± 1 SE) is shown in the box. There was no fresh litter at site F during sampling

(Fig. 3b). Bulk soil organic matter (SOM) showed substantial enrichment in ^{13}C with depth (Fig. 4) in the first 10 cm of soil at the wetter sites (B and C), which have a more developed soil profile. The $\delta^{13}\text{C}$ of SOM was fairly constant at all sites below 10 cm depth. In general, the wettest of the year 2000 sites (*Picea-Tsuga*, site B) had the most negative SOM values and the driest site (*J. occidentalis*, site F) the most positive. Below 10 cm, the SOM $\delta^{13}\text{C}$ values were indistinguishable at the *Picea-Tsuga* (B), *P. menziesii* (C), and *P. ponderosa* (E) sites. Within each site, there was a large enrichment in ^{13}C between fresh and old litter at three of the sites, and between litter and SOM at the wetter sites (Fig. 4).

Relationship between $\delta^{13}\text{C}_R$ and *vpd*

Strong correlations were observed between *vpd* and $\delta^{13}\text{C}_R$ at all sites where *vpd* data were available (C, D, E, and F), with the correlation coefficient in some cases approaching 1 after a time shift (Fig. 5). There were broad general peaks in the correlation coefficient that appeared at consistent time shifts regardless of the averaging time. In some cases, multiple peaks were observed (sites D and F) that corresponded with different time lags, while in others, a single peak was apparent (site E).

Two-week time series of half-hourly *vpd* at the *P. ponderosa* (E) site are shown in Fig. 6. These include the sampling periods with the maximum (–24.2‰) and minimum (–27.7‰) observed Keeling plot intercepts at this site. Arrows denote the nights when air sampling occurred (lined up on the *x*-axis for comparison purposes), and the shaded boxes indicate the 5-day shift and 2-day

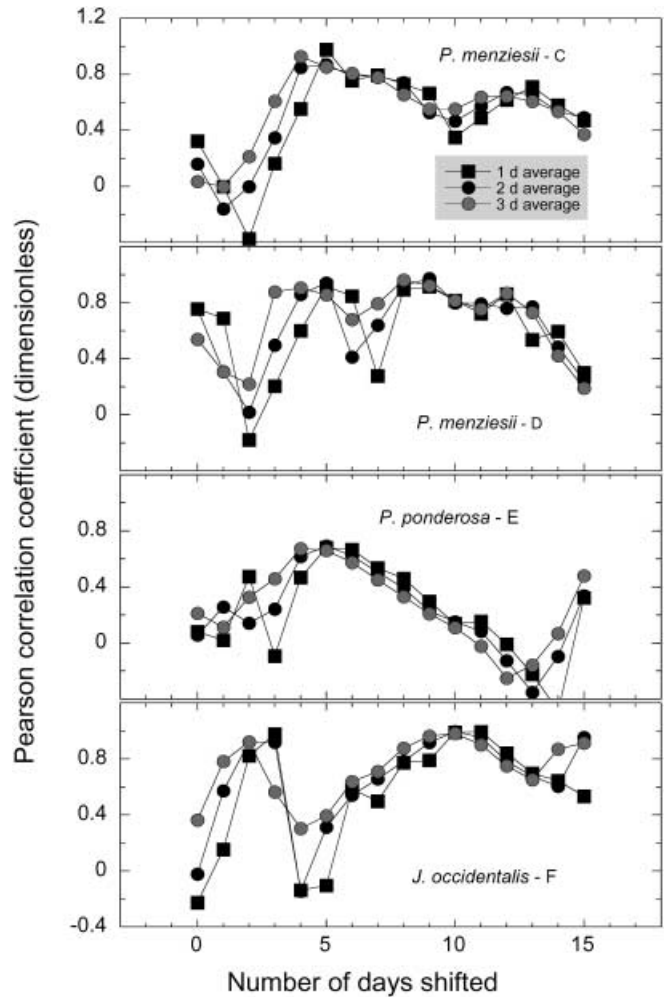


Fig. 5 Pearson product-moment correlation coefficients for linear regressions of $\delta^{13}\text{C}_R$ versus (averaged and time-lagged) air vapor saturation deficit (*vpd*). *vpd* data used in this and subsequent analyses are daytime hours only, and recent freeze events are excluded. The different symbols in the legend correspond to number of days averaged, and the abscissa corresponds to number of days shifted back in time, relative to the date of air sampling. A 1-day average with a 0-day shift corresponds to the *vpd* on the day immediately preceding sampling (all sampling occurred at night)

average that provided the maximum correlation in Fig. 5. These boxes indicate the relevant *vpd* events associated with observed $\delta^{13}\text{C}_R$ values. Note that the most positive $\delta^{13}\text{C}_R$ was associated with strong atmospheric demand (high *vpd*), and the most negative with the lowest *vpd*.

Selecting the shift (5, 9, 5, and 10 days for sites C, D, E, and F, respectively) that provided the maximum correlation in Fig. 5 for a 2-day average, $\delta^{13}\text{C}_R$ is plotted versus *vpd* for all four sites in Fig. 7. A consistent relationship is apparent for all sites, and within each site, there was a wide range of $\delta^{13}\text{C}_R$ and associated *vpd* values. There were ten sampling periods at the *P. ponderosa* and *J. occidentalis* sites that deviated significantly from the pattern shown in Fig. 7; these points are not shown explicitly in the figure, but their location is indicated by the ellipse in the upper left corner. All of these sampling pe-

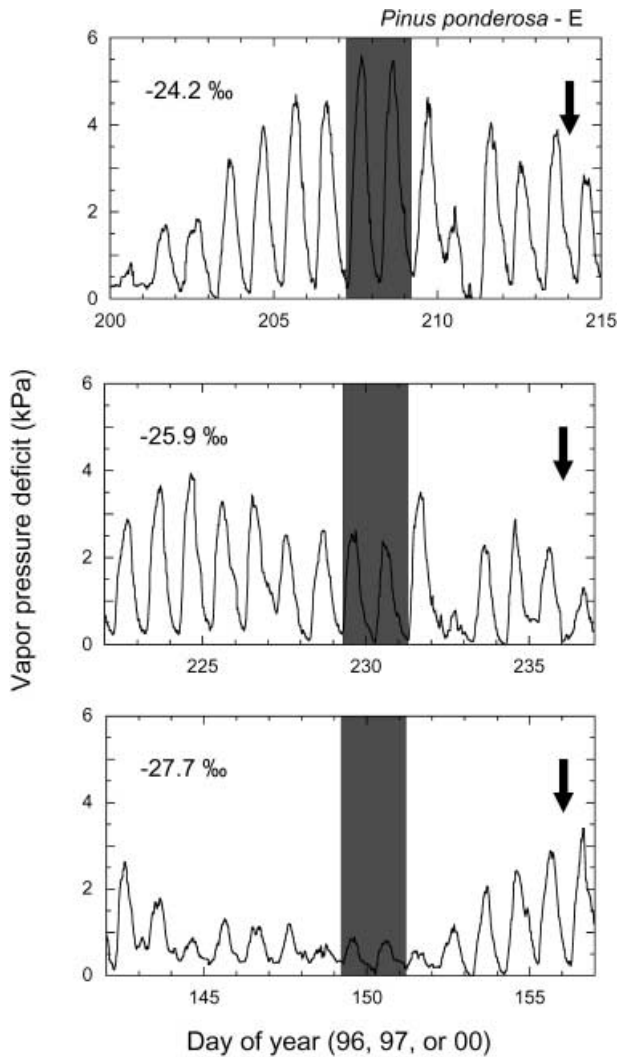


Fig. 6 Time series of half-hourly air vapor saturation deficit for the 2-week period preceding air sampling on selected nights at the *P. ponderosa* site, showing the events of importance in determining $\delta^{13}\text{C}_R$. The most positive and most negative $\delta^{13}\text{C}_R$ data at this site are shown, along with an intermediate point. The night of air sampling in each case is denoted with an *arrow*, and the *shaded box* corresponds to the 2-day average and 5-day shift that provided the maximum correlation in Fig. 5. $\delta^{13}\text{C}_R$ values for each sampling night are indicated on each plot

riods occurred during or just after a period of freezing temperatures. There is a clear distinction between sampling periods with versus without freezing air temperatures. (The apparent outlier at the ponderosa pine site within the ellipse in Fig. 7 was not associated with a recent freeze, but falls within the region associated with other freeze events.)

Conductance

Leaf diffusive conductance, estimated from the $\delta^{13}\text{C}_R$ values, decreased as *vpd* increased (Fig. 8). This is consistent with observations of stomatal responses to *vpd*

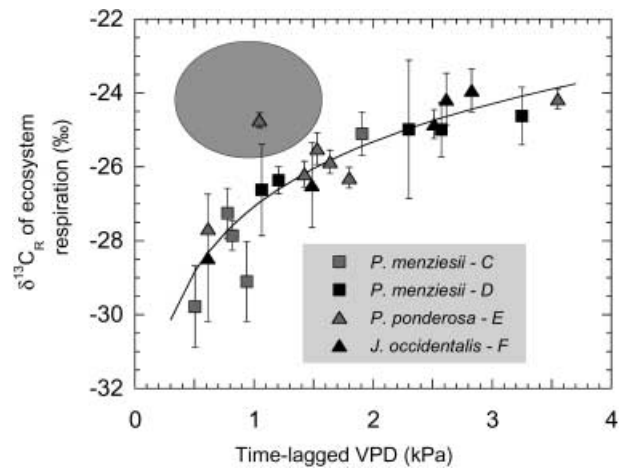


Fig. 7 Relationship between the carbon isotopic composition of ecosystem respiration and (averaged and time-lagged) air vapor saturation deficit. Two-day averages were used in each case, and time lags of 5, 9, 5, and 10 days were used for the *P. menziesii* (C), *P. menziesii* (D), *P. ponderosa* (E), and *J. occidentalis* (F) sites, respectively. The effect of recent freeze events (minimum air temperature $<0.2^\circ\text{C}$ in the last 7 days) on Keeling plot intercept is indicated by the *ellipse*; all data points which were excluded from the *vpd* analysis due to recent cold temperatures fall within the ellipse. Of the 33 Keeling plot intercepts at these four sites shown in Fig. 2, 10 were omitted here due to recent freeze events, and 2 were omitted due to missing weather data. The line drawn is a simple logarithmic fit ($y=2.54\ln x-27.08$, $r^2=0.79$, $n=22$)

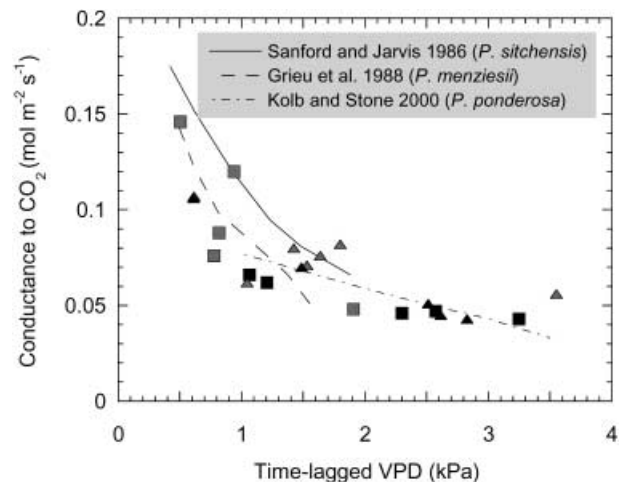


Fig. 8 Total (stomatal+boundary layer) conductance to CO_2 versus air vapor saturation deficit. Conductance was estimated from *A-c_i* curves for each species using the approach of Farquhar and Sharkey (1982), with c_i/c_a derived from the Keeling plot intercepts, assuming $c_a=360$ ppm. Also shown are leaf-level stomatal conductance-*vpd* relationships adapted from Sanford and Jarvis (1986), Grieu et al. (1988), and Kolb and Stone (2000) for three of our study species

from the literature made on individual leaves for three of our study species.

Discussion

Consistent patterns were found between precipitation and the carbon isotope ratios of plant tissues, soil organic

components, and ecosystem respiration. In general, the drier sites exhibited more positive $\delta^{13}\text{C}$ than the wetter sites (Figs. 3, 4). This is consistent with our hypothesis that site water availability affects stomatal conductance, which is reflected in photosynthetic discrimination differences between the sites, and ultimately affects the isotopic content of carbon released during respiration.

Several other studies have examined the variation in isotopic composition of plant tissues across moisture or humidity gradients (Guy et al. 1980; Farquhar et al. 1989; Stewart et al. 1995; Schulze et al. 1996a, 1996b, 1998). Stewart et al. (1995) examined leaf carbon isotope ratios for hundreds of herbaceous and arboreal species in 12 communities across a rainfall gradient in eastern Australia. Leaf $\delta^{13}\text{C}$ for individual species, as well as community averages at each site, were strongly negatively correlated to precipitation. In contrast, Schulze et al. (1998) found that community-averaged leaf-level discrimination of a wide variety of tree species along a northern Australian moisture gradient was constant at rainfalls above 475 mm. The lack of significant change in $\delta^{13}\text{C}$ at the community scale with changing rainfall was also observed in Patagonian ecosystems consisting of several plant functional types (Schulze et al. 1996b) and in C_4 grasses in relatively drier sites in Namibia (Schulze et al. 1996a). Schulze et al. (1998) suggested that (for their northern Australian transect), changes in species composition may have acted to maintain a relatively constant carbon isotope discrimination across a rainfall gradient.

The results of the present study (Figs. 3, 4) suggest that there is substantial variation in discrimination based on water availability in coniferous forests in Oregon. While several of our sites have been logged within the last 30 years (sites B, C, D), the dominant species at each site are natives and consistent with those in natural ecosystems of Oregon with similar rainfall amounts. We did not find major differences in ^{13}C content of SOM at depth at all sites (Fig. 4), which would be a strong indicator of community-level differences in photosynthetic discrimination between sites over a long time period. However, differences in $\delta^{13}\text{C}$ of leaf and root tissue support this hypothesis for the existing vegetation.

We found major differences in the isotopic signature of ecosystem respiration across the transect (Fig. 2), and the drier sites exhibited more positive $\delta^{13}\text{C}_R$ (Fig. 3a). This result is consistent with the notion that photosynthetic discrimination varies in response to availability of water to plants (Ehleringer and Cerling 1995), and that differences in discrimination are conferred to $\delta^{13}\text{C}_R$. The wettest site (A) was a distinct exception to this pattern. Site A is a 150-year-old mixed stand of *P. sitchensis* and *T. heterophylla*. Aboveground net primary production of forests is now well-established to decline with stand age (Ryan and Waring 1992; Yoder et al. 1994; Gower et al. 1996), and decreasing aboveground production in this stand has been directly confirmed (Harcombe et al. 1990). While the reasons for decline in productivity with

age are an area of active research (Ryan and Yoder 1997; Becker et al. 2000), hydraulic limitations to water uptake in old trees have been directly implicated (Hubbard et al. 1999). Changes in hydraulic conductance have been shown to affect stomatal conductance (Hubbard et al. 2001) and leaf $\delta^{13}\text{C}$ (Panek 1996), and the ecosystem-wide carbon isotope discrimination at site A has likely decreased with age. Similar enrichment in $\delta^{13}\text{C}_R$ with increasing stand age has been observed in *P. menziesii* forests ranging in age from 20 to >450 years in Washington, USA (J.E. Fessenden and J.R. Ehleringer, unpublished data). While the overstory trees in our *P. ponderosa* and *J. occidentalis* sites are also old (Table 1), each has a much younger age component in the stand, and our air samples contain CO_2 from all respiring components. Because water is more limiting at these sites, the influence of water availability is potentially more important than stand age in determining $\delta^{13}\text{C}_R$.

Examining individual periods across all sites, variations in $\delta^{13}\text{C}_R$ values were correlated most significantly with precipitation during the month preceding sampling, but also with leaf predawn water potential and soil water content (Table 2). Even so, a component of the overall variation in $\delta^{13}\text{C}_R$ was not explained by these factors. Within a site, each of these variables had limited predictability in accounting for the variability in $\delta^{13}\text{C}_R$ (site C was an exception for precipitation; Table 2). Across any extreme climatic gradient, substantial covariation in environmental and biological factors is expected; such similarities do not necessarily imply a causal relationship. However, the combination of the leaf, root, litter, and SOM isotope data, and the observation that mean $\delta^{13}\text{C}_R$ is strongly correlated with mean annual precipitation, strongly implicates differences in photosynthetic isotope discrimination across the Oregon transect as the cause for observed variation in $\delta^{13}\text{C}$ of carbon stocks and fluxes.

There are at least three possible mechanisms that could cause variation in $\delta^{13}\text{C}_R$ within a given ecosystem over time. First, since respiration rates in general are strongly dependent on temperature, seasonal or diurnal changes in air and soil temperatures may change the relative contributions of each ecosystem component (root respiration and decomposition belowground, litter decomposition, foliar and sapwood respiration) to the total ecosystem respiration flux. These changes might result solely from changes in the balance of the component flux rates and do not necessarily involve changes in the isotopic composition of the components of the CO_2 flux. Second, the isotopic signatures of the components of the respiration flux may change over time. For example, soil moisture at our sites changes dramatically throughout the year (Gholz 1982; Miller et al. 1992; Anthony et al. 1999; Law et al. 2000), affecting C and N mineralization rates and altering the organic substrates available for decomposition. Activity of soil microbes, macrofauna, and mycorrhizae are likely to differ seasonally in response to soil moisture and nutrient availability (e.g., Law et al. 2001), and their isotopic contribution to the total ecosys-

tem CO₂ flux will change as different substrates are utilized. Third, photosynthetic discrimination may change in response to changes in environmental factors such as irradiance, air temperature, and humidity. Bulk leaf $\delta^{13}\text{C}$ has long been used as an indicator of photosynthetic discrimination, and variation of leaf $\delta^{13}\text{C}$ within year 2000 at our sites was minimal (data not shown, but see standard errors in Fig. 3b). However, leaf $\delta^{13}\text{C}$ provides a long-term estimate of leaf Δ during the time that the carbon in leaves was fixed, and that is a poor indicator of day-to-day variability in c_i/c_a (Brooks et al. 1997). The isotopic content of phloem sap has been shown to be related to seasonal rainfall patterns in *Eucalyptus globulus*, in a manner consistent with expected seasonal changes in Δ (phloem sap $\delta^{13}\text{C}$ was more positive during water stress; Pate and Arthur 1998).

The ^{13}C content of ecosystem respiration in the present study was not correlated with nocturnal air temperature either across or within sites (Table 2), but was strongly correlated with *vpd* at all sites where this comparison was possible (Figs. 5, 6). The correlation with daytime *vpd* on the day that sampling occurred (1-day average, 0-day shift, Fig. 5) was generally weak, but strong correlations were apparent with the *vpd* some days before sampling (5- to 10-day shift, Fig. 5). Stomatal conductance and photosynthetic discrimination are directly affected by changes in humidity (Madhavan et al. 1991; Comstock and Ehleringer 1992; Ehleringer and Cerling 1995), and recently produced leaf starch and sugars are closely linked to c_i/c_a (Brugnoli et al. 1988). Thus photosynthate produced during periods of water stress is likely to be enriched in ^{13}C . To the extent that recently fixed photosynthate is used as a substrate for respiration, either above or below ground, such signals might be apparent in the ^{13}C signature of the ecosystem respiration flux some time later.

However, when such a signal might be expected in the integrated respiration flux of an ecosystem is unclear. Clearly, some lag would be expected, since such factors as phloem loading, phloem transport time, phloem unloading, plant carbon allocation, leaf and root phenology, root exudation, mycorrhizal and microbial activity, and fine-root turnover must all play a role. There is some indication of reasonable timing expectations in the literature. Horwath et al. (1994) radiolabeled small (3-m) *Populus* trees, and found a peak in ^{14}C activity of the soil respiration flux 2 days later, along with a smaller, second peak after 10 days. A similar experiment with *Populus* found ^{14}C in the soil CO₂ flux several hours after labeling, with a peak after 3–4 days (Mikan et al. 2000). Root growth and respiration rate in grasslands are dependent on the cumulative solar radiation flux 2–10 days earlier (Fitter et al. 1998, 1999), and a ^{13}C label applied to the air of a 15-year old *Pinus taeda* forest in North Carolina, USA, was detected in the soil respiration flux within 1 week of fumigation (Andrews et al. 1999).

We found peaks in the correlation coefficients between $\delta^{13}\text{C}_R$ and *vpd* at 5, 9, 5, and 10 days for sites

C–F, respectively (Fig. 5). These are compatible with the time periods mentioned in the above studies; thus, the respiration flux from an ecosystem likely consists in large part of recently fixed carbon (assimilated within the last 10 or so days). This is in direct agreement with Ekblad and Höglberg (2001), who found a distinct correlation between atmospheric humidity and the isotopic signature of soil-respired CO₂ 2–4 days later, in a boreal mixed coniferous forest in Sweden.

We do not expect a single lag time to be associated with a given forest. Since the rate of translocation of photosynthate is likely dependent on temperature, the time for fixed carbon to be exuded by the roots or consumed by rhizospheric bacteria or distant mycorrhizae is not likely to be fixed. We would expect the isotopic signature of foliar respiration to respond much more quickly to a given atmospheric stress event than heterotrophic respiration in the soil that might be dependent on root exudates. Furthermore, the amount of carbon accumulated will differ under differing weather events, since assimilation is so strongly linked to light availability. The fact that there is not a single, obvious lag time at each site (Fig. 5) is probably a consequence of these factors. However, no matter which lag time is chosen, there is almost always a high degree of correlation between $\delta^{13}\text{C}_R$ and *vpd* (Fig. 5).

Examination of the most extreme $\delta^{13}\text{C}_R$ periods at the *P. ponderosa* site (Fig. 6) suggests that the isotopic signature of the respiration flux may be quite dynamically linked to recent meteorological events. A period with high *vpd* was followed 5 days later by a fairly positive respired CO₂ signature (–24.2‰). In contrast, a relatively cool moist period was associated with more negative $\delta^{13}\text{C}_R$ (–27.7‰; Fig. 6). Anthony et al. (1999) have shown that this forest exhibits interesting shifts in the balance between photosynthesis and respiration during the summer. During a year of extreme drought (half the normal annual rainfall), hot dry days resulted in a net daily release of CO₂ via respiration, and cool, humid periods were associated with net uptake. Air temperature and *vpd* can change markedly over the span of a few days, and the isotope ratio of respired CO₂ appears to change concomitantly. This *P. ponderosa* forest canopy is very open, with a one-sided leaf area index of 2.1 m² m^{–2} (Law et al. 2001). About 75% of annual ecosystem respiration (R_e) comes from root and microbial respiration in the soil, and 20% from foliage. Autotrophic respiration accounts for ~55% of annual R_e (Law et al., in press), suggesting that only half of the respiration response to *vpd* was from autotrophs.

The individual $\delta^{13}\text{C}_R$ values for all time periods in the analysis are shown in Fig. 7, plotted versus the time-lagged *vpd* that provided the highest correlation for each forest (individually) in Fig. 5. A consistent relationship was found across all four sites. These sites range in mean annual precipitation by nearly an order of magnitude (Table 1), their mean $\delta^{13}\text{C}_R$ differs quite strongly with precipitation (Fig. 3a), and yet a similar *vpd* relationship is apparent for all. Circled in Fig. 7 is the loca-

tion of the data points excluded from the *vpd* analysis (a total of ten time periods, all from the *P. ponderosa* or *J. occidentalis* sites). These periods were associated with recent freeze events, and in every case, the isotope ratio of respired CO₂ was more enriched than the *vpd* relationship would predict. This is likely a result of prolonged stomatal closure following cold air temperatures, which has been observed in several conifers in the Rocky Mountains of the United States (Smith et al. 1984, and references therein).

Notable in Fig. 7 is the lack of data below and to the right of the line. Assuming that stomatal closure in response to *vpd* is influencing Δ , and that this result is transferred to $\delta^{13}\text{C}_R$, data points in this region would indicate exceedingly high stomatal conductance for a given *vpd*. The absence of data in this region is consistent with a hydraulic operational setpoint, whereby plants regulate stomatal aperture to prevent embolism of xylem conduits in either the shoots or the roots (Tyree and Sperry 1988; Hacke et al. 2000).

If photosynthetic discrimination indeed changes in response to atmospheric humidity, then $\delta^{13}\text{C}_R$ should reflect to some degree the stomatal or canopy conductance of the entire ecosystem. When conductance to CO₂ is estimated using $\delta^{13}\text{C}_R$, a realistic relationship with time-lagged *vpd* emerges (Fig. 8). Conductance is highest at low *vpd* and declines substantially as *vpd* increases. These $\delta^{13}\text{C}_R$ -derived estimates of conductance are directly comparable in magnitude to leaf-level observations from the literature for three of our study species (Fig. 8). We were unable to find leaf area-based *g-vpd* curves for *T. heterophylla* or *J. occidentalis* in the literature, but Law and Waring (1994) reported full stomatal closure at 1.4 kPa for *J. occidentalis*. We stress that our purpose was not to use isotopic measurements to evaluate ecosystem conductance. Rather, we use the conductance/*vpd* relationship to demonstrate the likelihood of Δ changing in response to atmospheric humidity deficits. This is a necessary condition to support our assertion that Δ is changing and that this change is reflected in respired CO₂ some time later. If this is correct, then we stand to gain considerable insight about ecosystem physiology from analyses of Keeling plots.

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