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Continental and local climatic influences on hydrology of eucalypt-*Nothofagus* ecosystems revealed by $\delta^2\text{H}$, $\delta^{13}\text{C}$, and $\delta^{18}\text{O}$ of ecosystem samples

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[1] Marrying knowledge of variation in large-scale climatic parameters such as rainfall and evaporation to physiological ecology has long been argued as a powerful approach to advancing understanding of hydrology of catchments. Widely used hydrological models for assessing water yield depend on key plant attributes such as whether or not plant water use is coupled to atmospheric and/or soil water status. We analyzed $\delta^2\text{H}$ and $\delta^{18}\text{O}$ signatures of long-term rainwater collections from coastal sites near Melbourne, Australia, and in northwest Tasmania and compared them with their counterparts in rainwater, stream water, soil water, and twig water data collected over a 2 year period from south facing *Eucalyptus-Nothofagus* forests in the Cement Creek catchment of Mt. Donna Buang, about 70 km east of the city of Melbourne. Within the catchment, progressive evaporative enrichment among rain, soil, and twig water accounted for observed $\delta^2\text{H}$ and $\delta^{18}\text{O}$ signatures. We observed a major shift in both $\delta^2\text{H}$ and $\delta^{18}\text{O}$ signatures of rain and stream water between 2001/2002 and 2003. The shift was likely due to changes in atmospheric conditions and especially relative contributions to rainwater from oceanic and continental sources. Our plant isotope data argue strongly that radiation, not water, is a primary limitation for *Nothofagus* on Mt. Donna Buang. The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signatures of foliage varied with season and with topography. For the wettest and driest years in the 1978–2000 record, strong and consistent altitudinal gradients in $\delta^{13}\text{C}$ of tree rings had a slope of between 4‰ and 5‰ km⁻¹ of altitude. Our data highlight the importance of background (e.g., rainfall and atmospheric CO₂) isotope data to interpretation of plant isotope data. Taken together with the literature, our isotope data lead us to conclude that (1) in periods of close to average rainfall, the observed meteoric water line at Mt. Donna Buang and at other stations in southeast Australia departs strongly in slope and intercept to that observed for rainfall collected within reasonable proximity of oceans worldwide, due mainly to contributions of rainfall that originate in airstreams from the far northwest of the Australian continent (the Indian Ocean) and (2) in drought periods, the failure of such continentally influenced rainfall ensures local meteoric water lines exactly match those recorded elsewhere for near-coastal regions. Finally, the hydrologic behavior of eucalypt forests varies strongly, from typically water-limited conditions that require more complex modeling (i.e., including a significant climatic influence on plant water use), to areas where stomatal conductance, and hence transpiration, is not constrained by water availability, and modeling may be more simply based.

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1. Introduction

[2] Analysis of pairs of stable isotopes (e.g., H/O, O/C, C/N) in natural waters and plant tissues and fluids can provide important, even critical information about hydrological cycles at the ecosystem scale [Mook, 2006; West et al., 2006]. The abundances of stable isotopes of H and O ($\delta^2\text{H}$ and $\delta^{18}\text{O}$) in water samples are usually compared with their strong, linear relationship in rainfall around the globe: the Global Meteoric Water Line (GMWL) [Craig, 1961; Dansgaard, 1964; Craig and Gordon, 1965]. Locally, that

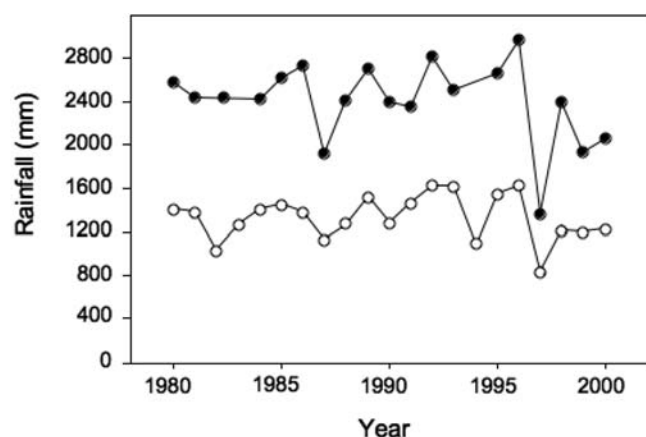


Figure 1. Twenty year records of annual rainfall for Warburton Post Office (open circles) and Mt. Donna Buang (closed circles). See text for further details.

relationship may vary, especially according to altitude and distance from coastlines [Clark and Fritz, 1997] and also throughout the seasonal cycle of 1 year [Gat, 1996]. Similarly, knowledge of the background abundance of stable isotopes in the atmosphere and in soil water and other natural waters (e.g., rainwater, groundwater, and stream water) is usually a prerequisite for reliable interpretation of plant isotope data [Sternberg, 1988; Farquhar and Cernusak, 2005]. The abundances of stable isotopes C ($\delta^{13}\text{C}$) in plant matter [e.g., Bowling *et al.*, 2008] are widely used as a guide to stomatal conductance, to water vapor at the time of carbon fixation, and may thus be a guide to the plant water use component of hydrologic models.

[3] Stable isotopes have significant potential application in developing our understanding of the contributions of different geographic parts of catchments to stream water and thus water yield [Bowen and Revenaugh, 2003; Kendall and Coplen, 2001]. Yet for nearly all eucalypt-dominated catchments, we lack any significant knowledge of background influences on isotopic composition of stream water or of plant organic matter. For example, eucalypt-dominated, mountainous landscapes are crucial water catchments for the city of Melbourne and on southerly and sheltered aspects may contain a significant component of *Nothofagus cunninghamii*. While we know broadly that altitude affects the carbon isotope signature of wood and foliage of both softwood and hardwoods [Körner *et al.*, 1991; Warren *et al.*, 2001], we know little about other, nonclimatic influences. In one study, Read and Farquhar [1991] measured the stable carbon isotope discrimination ($\delta^{13}\text{C}$) in foliage sampled from *Nothofagus* spp. in five Southern Hemisphere countries and found a strong relationship to summer (December–March) rainfall. That relationship was, however, the “opposite of the direct environmental effects one observes with decreasing water availability in a single species” [Read and Farquhar, 1991, p. 693]. Read and Farquhar’s work provided a clear hypothesis that $\delta^{13}\text{C}$ of organic matter of *Nothofagus* does not provide a reliable measure of stomatal conductance (or canopy conductance and thus transpiration) for catchments or subcatchments dominated by eucalypt-*Nothofagus* stands.

[4] We sought to demonstrate the utility of isotopic signatures of ecosystem samples in testing two of the most widely and long held ideas about the nature of eucalypt catchments in southeastern Australia. First, we sought to test the hypothesis that a significant portion of rainfall in the southeast arises from the influence of the Indian Ocean and variation in that source of water [Whetton, 1988; Nicholls, 1989]. Second, we sought evidence to test assumptions made by many water yield models used with eucalypt forests [e.g., Silberstein, 2006; Vertessy *et al.*, 1996], that tree water use (transpiration) is regulated in accordance with water availability in the soil and atmosphere.

2. Materials and Methods

2.1. Field Sites

[5] Study sites were selected on the south facing slopes of the Mt. Donna Buang massif, between the township of Warburton in the valley immediately to the south (~150 m above sea level (asl)) and the summit (~1240 m asl). The climate of this region of Australia is broadly defined as Mediterranean but rainfall in the highlands to the east of Melbourne is rather more uniformly distributed. Hence, the mean long-term rainfall for the driest month (February) is about 70 mm and about twice that for the wettest month (September), depending on location. Each year at the summit, several frosts are usually recorded in each of the months of July, August, and September, and snowfalls are common over the same period. Snow may cover the ground at the summit for up to 6 or 8 weeks, though in most winters there are extended periods without snow cover. Mean daily maximum temperature at the summit in summer is about 20°C, and daily minimum in winter is about 1°C. Fog and condensation are possible sources of water in the dry summer months.

[6] Records of long-term annual rainfall for stations operating at Warburton (152 m asl), and near the summit of Mt. Donna Buang (1240 m asl) are shown in Figure 1.

[7] Rainwater sampling stations were located in canopy openings at 1250, 1160, 1049, 980, 916, 798, 650, 531, and 240 m elevation (asl). Stream water was sampled from Cement Creek at elevations of 1042, 937*, 791, 696*, 562, 468*, and 240 m. Sampling stations marked with a * correspond to the three transects identified in Table 1. Soil samples were collected by auger in intervals of 0–15, 15–35, 35–60, 60–110, and 110–150 cm. At several sampling points, the soil profile did not extend beyond 35 cm.

[8] Vegetation study sites (Table 1) included five stands of *N. cunninghamii* at higher altitudes on relatively flat terrain, and on steeply sloping sites at lower altitudes, covering close to 800 m in elevation. We also sampled a second set of three, 150 m long, transects spanning Cement Creek at different altitudes (Table 1). In these transects, *N. cunninghamii* was a codominant together with *Atherosperma moschatum* and *Acacia melanoxylon*. Each transect contained three sampling locations (a set on each side of Cement Creek) that varied in distance (location 1 = minimum distance (always <5 m), location 3 = maximum distance (up to 100 m), location 2 = midpoint between minimum and maximum) from Cement Creek.

Table 1. Location and Characteristics of Study Sites at Mt. Donna Buang

Sample Set	Plot/Transect Number	Elevation (m)	Longitude	Latitude	DBH ^a (cm)
Plots	1	1220	145°40'45	37°42'27	34, 26, 27
	2	1153	145°40'22	37°42'50	36
	3	916	145°41'45	37°43'46	40, 29, 31
	4	650	145°42'32	37°42'53	37
	5	530	145°42'58	37°43'17	27, 34, 51
Transects	1	937–998	145°41'36	37°42'25	40, 35, 34, 25, 18, 31
	2	689–764	145°42'17	37°42'44	28, 27, 26, 26, 22, 21
	3	481–541	145°43'04	37°42'56	21, 31, 37, 24, 34, 30

^aDiameter at breast height over bark of sample trees. Three trees were sampled except at plots 2 and 4 where only one tree was sampled. Two trees were sampled at each of three distances from Cement Creek at transect sites. Diameters are shown in order of increasing distance from the creek.

2.2. Field Sampling

[9] Rain gauges and stream water sampling stations were established in October 2002, and rainwater and stream water samples were collected in November, December, February, March, May, June, and September. Rain gauges were supplied with an oil film to minimize evaporation of the rainwater collected. Not all gauges or sampling stations could be reached at every sampling date owing to local conditions (e.g., snowfall and treefall). A total of 50 samples of stream water and 70 samples of rainwater were collected and analyzed.

[10] Twigs and foliage were collected in November and December (summer collections) and again in July and August (winter). Twigs (and attached foliage) were collected using long-handled clippers. Trees were climbed where necessary to ensure that samples were collected from sunlit parts of the canopy. At least two foliage samples (each representing several twigs) were collected for each location on each transect at each sampling date. In summer, xylem water from the twigs was extracted immediately using a hand vacuum pump according to the method described by *Bollard* [1960; see also *Brandes et al.*, 2007]. Water samples collected from individual twigs were kept separate and a total of 56 samples were available for analysis. No xylem water was collected in winter. For comparison with soil water, a total of 63 soil samples were collected in summer, roughly equally divided between the two sampling dates. Soils were sampled at each of the three locations on the three transects.

[11] Stem cores were taken at breast height from sample trees between August and October 2001. A hand auger was used, and care was taken to extract intact cores to the full depth. Holes were back-filled and treated with a fungicide. A total of 29 cores were collected and analyzed separately (see also Table 1).

[12] All samples (water, soil, foliage, and wood) were carefully handled in the field to prevent evaporation. Sample bottles for water were always filled (using varying size bottles if required) and tightly capped, and soil samples were stored in zip-locked bags, as were foliage samples. Rainfall gauges were prone to fouling, and any contaminated samples were discarded. Wood cores were placed in plastic centrifuge tubes of similar volume. All samples were kept in insulated containers until they could be transferred to refrigeration units at our laboratory (2–3 h travel).

2.3. Sample Preparation and Analysis

[13] Water samples (including twig water) were analyzed as collected, without further preparation. Soil water was

distilled cryogenically and duplicate distillations were performed for ~10% of all samples to check for artifacts. Leaves were dried at 65°C, homogenized, and aliquots of approximately 1 mg were used for isotopic analysis. Isotopic abundances for hydrogen and oxygen in water and foliage were determined as described in detail by *Brandes et al.* [2007].

[14] Isotope data are represented in δ format (‰): $\delta^{XX}E = (R_{\text{sample}}/R_{\text{standard}}) - 1$, where R is the ratio of heavy to light isotope, E is the element of interest, and the primary standards were Vienna Pee Dee Belemnite (VPDB) and Vienna Standard Mean Ocean Water (VSMOW). Additional data on the isotopic composition of rainwater collected at nearby long-term monitoring stations was sourced from the International Atomic Energy Agency Web site (Global Network of Isotopes in Precipitation, The GNIP Database, 2004, available at <http://isohis.iaea.org>) Data are available for two stations in southeast Australia: Melbourne (discontinued in 1998) and Cape Grim (northwest Tasmania).

[15] Stem cores were air-dried at about 21°C for 3 months. They were then polished using an air-bedded molding cutter. Care had to be taken to ensure that tree rings were maintained in the vertical position such that the polished core showed the exact ring width of each year. All cores were processed to the polished stage. Only cores showing distinct growth rings for the surveyed time span were used in dendrochronological analysis at the Institute for Forest Growth, Freiburg, Germany. After identification of the diameter of each ring for the 20–25 years of interest, a sample of late wood was extracted from each year ring [*Macfarlane and Adams*, 1998]. These samples were prepared for carbon isotope analysis carried out with a Delta plus isotope ratio mass spectrometer (ThermoFisher, Bremen, Germany) coupled to an elemental analyzer as described by *Gessler et al.* [2001].

2.4. Statistical Analyses

[16] Data were analyzed using commercially available software. Statview and SuperANOVA (Abacus Concepts Inc.) were used for Analysis of Variance (ANOVA), while Genstat V was used for all other analyses; namely, means, standard errors, and linear correlations. Differences in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ of leaf material as a consequence of transect elevation, distance of sample location from creek, and season were tested with 3-way ANOVA. One-way ANOVA were used to determine if differences in tree ring widths could be explained by an altitude effect, and also if $\delta^{13}\text{C}$ in latewood

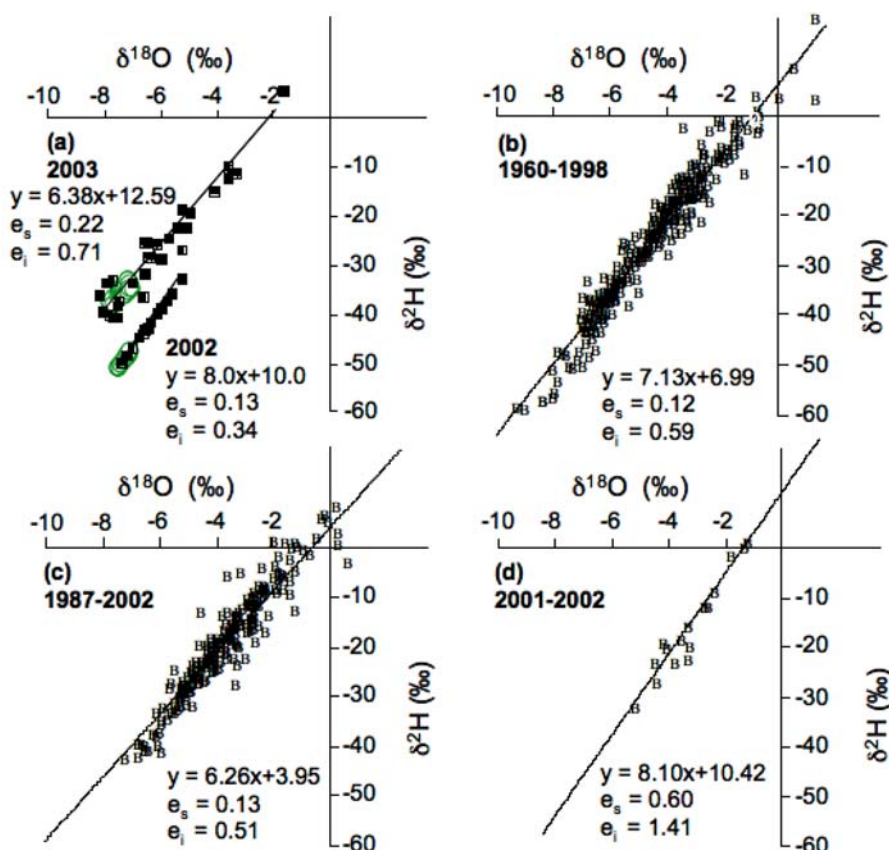


Figure 2. Relationships between $\delta^2\text{H}$ and $\delta^{18}\text{O}$ in rain (closed squares) and stream water samples (open circles) from (a) the Cement Creek catchment at Mt. Donna Buang and in rainwater samples (“B”) collected near (b) Melbourne and at (c, d) Cape Grim in northern Tasmania. Within plots, linear regression equations are given, including the error on the slope (e_s) and the error on the intercept (e_i).

was affected by altitude. Significance for all analyses was set with $p < 0.05$.

3. Results

3.1. The $\delta^2\text{H}$ and $\delta^{18}\text{O}$ in Rain, Stream, and Twig Water

[17] Rainwater samples separated clearly (Figure 2) into two time periods: samples collected in late 2002 and all other samples. This separation corresponds to the division between one of the worst recorded droughts in southeastern Australia (2001/2002) and a period of more normal rainfall (2003). The 2001/2002 drought was followed by bushfires that consumed more than a million hectares of forested land.

[18] The $\delta^2\text{H}$ and $\delta^{18}\text{O}$ of rainwater samples collected in 2002 were linearly related (Figure 2a) with a slope of 8 and an intercept of 10, i.e., identical to the Global Meteoric Water Line (GMWL). This linear regression explained 94% variation (r^2) within the data set, where the error on the slope (e_s) was only 0.22, and the error on the intercept (e_i) was 0.71. Rainwater collected in 2003 departed significantly from the GMWL, and the linear relation between $\delta^2\text{H}$ and $\delta^{18}\text{O}$ had a slope of 6.4 and an intercept of 12.6 ($r^2 = 1$, $e_s = 0.13$, $e_i = 0.34$). Stream water matched (with no difference in slope or intercept) the rainwater samples in isotopic composition when also divided into samples collected in 2002 and those collected in 2003 (Figure 2a). Isotopic

abundances in stream water varied far less (not more than 1‰ ^{18}O and not more than 5‰ ^2H) than those in rainwater and were tightly clustered at the depleted end of the rainwater range.

[19] Independent data sets from long-term rainwater monitoring stations revealed similar patterns. Data from the Melbourne station (70 km to the west) for the years 1960–1998 reveal a slope for the $\delta^2\text{H}:\delta^{18}\text{O}$ relationship of 7.1 and an intercept of 7 ($r^2 = 0.93$, $e_s = 0.12$, and $e_i = 0.59$; see Figure 2b). Similarly, for the years 1997–2002, the $\delta^2\text{H}:\delta^{18}\text{O}$ relationship in rainwater at the Cape Grim station has a slope of 6.3 and an intercept of 3.9 ($r^2 = 0.92$, $e_s = 0.13$, and $e_i = 0.51$; see Figure 2c). Finally, when the data for the years 2001 and 2002 at Cape Grim are isolated (Figure 2d), the $\delta^2\text{H}:\delta^{18}\text{O}$ relationship in rainwater reverts to a slope of 8.1 and an intercept of 10.4 ($r^2 = 0.93$, $e_s = 0.60$, and $e_i = 1.41$), again almost identical to the GMWL.

[20] Isotopic abundances in soil water and twig water in summer 2002 are plotted in Figure 3, along with the Local Meteoric Water Lines (LMWL) for 2002 and 2003. The data show clear evidence of evaporative enrichment: from soils at depths greater than 15 cm to surface soils, and from surface soils to twigs. With the exception of two samples, all twig water was enriched in ^2H relative to ^{18}O when compared with rain or stream water (i.e., all samples showed greater $\delta^2\text{H}$ and $\delta^{18}\text{O}$, and there was a tendency for the slope of a

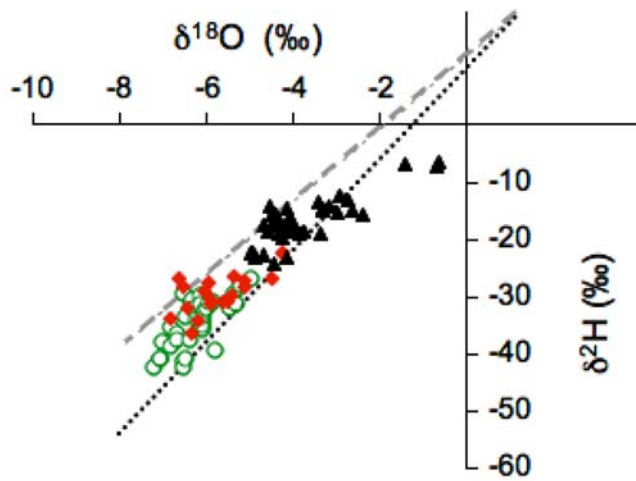


Figure 3. Relationships between $\delta^2\text{H}$ and $\delta^{18}\text{O}$ in soil water (0–15 cm: closed diamonds; >15 cm: open circles) and twig water (closed triangles) from *Nothofagus* stands within Cement Creek catchment, Mt. Donna Buang. Also shown are the Local Meteoric Water Lines for 2002 (dotted line) and 2003 (dashed line) (from Figure 2).

line connecting the twig water data points to be lower than the LMWL; see Figure 3).

3.2. The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in Foliage and Tree Rings

[21] Neither elevation nor distance from Cement Creek had a significant effect on either $\delta^{13}\text{C}$ or $\delta^{18}\text{O}$ of foliage (Table 2). On the other hand, the season of sampling had a highly significant effect on both. Foliage was significantly ^{13}C -depleted in summer relative to winter (Table 2), although both mean summer and winter $\delta^{13}\text{C}$ signatures were never greater than -28‰ . The $\delta^{18}\text{O}$ of foliage varied up to 10‰ from winter to summer, depending on transect and location, with an average winter-summer enrichment of 5.6‰ (Table 2).

[22] Annual growth of *N. cunninghamii* varied little across all study sites at Mt. Donna Buang (Table 3). There was a clear and highly significant ($p < 0.0001$) effect of altitude (Table 3) if the data were analyzed using altitude as the sole independent variable. The best growth was consistently recorded by trees growing on the summit plateau and by those at lower altitudes. Conversely, growth was least on the steep slopes at intermediate altitudes. Carbon isotope abundance of the late wood from tree rings was highly significantly ($p < 0.0001$; see Table 3) related to both altitude and structural formation (codominant or understory). The significance of the effect of altitude was dominated by intermediate altitude site that showed about a 1.3‰ increase in discrimination over the other three, broad altitudinal classes.

[23] Radial growth of *N. cunninghamii* (Figure 4) generally increased between 1979 and 1996 and then declined. This reflects the less than average rainfall in the latter half of the 1990s (Figure 1). As might be expected for trees spanning almost 800 m of altitude, numerous microclimatic zones, and a range of initial sizes, the variability around the mean for any given year is moderately large. Carbon isotope discrimination generally mirrored growth, increasing through the 1980s and 1990s before decreasing after about 1996 (Figure 4). Growth and carbon isotope signatures were significantly and linearly related ($\delta^{13}\text{C} = -0.009 \times (\text{width of growth ring}) - 24.2$, $r^2 = 0.37$, $p < 0.01$). Interpolated on the basis of site elevation and rainfall at the summit and at Warburton Post Office, annual rainfall was weakly related to growth or to $\delta^{13}\text{C}$ ($p < 0.05$, $r^2 = 0.03$; detailed results not shown). Growth and $\delta^{13}\text{C}$ were also independent of summer (December–February) rainfall.

[24] Despite considerable variation, altitude was a good predictor of $\delta^{13}\text{C}$ (Figure 5) in the wettest and driest years. Combining all data from all trees, except those growing poorly close to Cement Creek at the lowest altitudes, we found moderately strong relationships between $\delta^{13}\text{C}$ and altitude. These variables were significantly linearly related for both the four wettest and the four driest years within the

Table 2. The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ of Foliage From Trees Located at Varying Distances From Cement Creek Within Sampling Transects at Different Elevations^a

		Location Relative to the Creek ^d					
Average Transect Elevation ^b (m asl)	Season ^c	Closest		Intermediate		Furthest	
		<i>x</i>	SE	<i>x</i>	SE	<i>x</i>	SE
$\delta^{18}O$ (‰)							
968	Summer	9.17	2.53	19.21	2.37	19.91	4.35
	Winter	12.10	0.23	14.20	1.23	14.99	1.18
727	Summer	17.92	4.57	22.45	2.00	23.66	1.97
	Winter	15.90	0.76	15.85	0.08	13.90	2.62
511	Summer	16.33	4.23	17.64	4.63	18.19	5.67
	Winter	15.32	1.48	9.29	1.14	10.54	1.49
$\delta^{13}C$ (‰)							
968	Summer	-29.97	0.33	-30.00	0.66	-29.36	0.60
	Winter	-29.73	0.36	-28.20	0.32	-28.52	0.24
727	Summer	-30.60	0.62	-29.79	0.07	-29.23	0.22
	Winter	-28.55	0.96	-28.15	0.80	-28.54	0.24
511	Summer	-30.12	0.61	-30.59	0.53	-30.67	0.89
	Winter	-29.97	0.82	-28.04	0.53	-28.01	0.01

^aSummary of main effects from three-way Analysis of Variance (ANOVA) is shown. None of the interaction terms were significant.

^bANOVA results are as follows: For $\delta^{18}\text{O}$, $F = 42.12$ and $p = 0.148$. For $\delta^{13}\text{C}$, $F = 0.85$ and $p = 0.441$.

^cANOVA results are as follows: For $\delta^{18}\text{O}$, $F = 15.49$ and $p = 0.001$. For $\delta^{13}\text{C}$, $F = 27.17$ and $p < 0.001$.

^dANOVA results are as follows: For $\delta^{18}\text{O}$, $F = 0.07$ and $p = 0.917$. For $\delta^{13}\text{C}$, $F = 3.35$ and $p = 0.057$.

Table 3. Mean Ring Width and Carbon Isotope Composition of Late Wood for *Nothofagus cunninghamii* Growing Over a Range of Altitudes at Mt. Donna Buang, Victoria^a

Altitude (m)	<i>n</i>	Growth (Ring Width, μm)			$\delta^{13}\text{C}$ (‰)	
		<i>x</i>	SE		<i>x</i>	SE
1000+	57	341	15		-26.90	0.12
~900	40	273	16		-26.74	0.12
~700	16	211	21		-28.08	0.18
~500	77	289	16		-26.72	0.14

^aRings within trees were regarded as independent. Mean is for all years 1978–1997. One-way ANOVA results are as follows: For $F = 5.94$, $p < 0.0001$; for $F = 5.83$, $p = 0.0007$ (see explanation of ANOVA in section 2.4).

record. The relationship was strongest for the wetter years when altitude explained almost 60% of variation in $\delta^{13}\text{C}$ (Figure 5).

4. Discussion

[25] The difference in slopes and intercepts of the local meteoric water lines (LMWL) between late 2002 and 2003 (Figure 2a) is remarkably strongly supported by the data for other stations in southeast Australia. The long-term data for samples from Melbourne (some 50 km to the southwest; see Figure 2b) and Cape Grim (on the northwest tip of Tasmania; see Figures 2c and 2d) was collected by the CSIRO. In the drought years of 2001 and 2002, the $\delta^{18}\text{O}$ signatures of rainfall from Mt. Donna Buang (as sampled and analyzed by us) and from Cape Grim (as sampled and analyzed by CSIRO) were linearly related (with high precision in the case of Mt. Donna Buang) to the $\delta^2\text{H}$ signatures, with a slope of 8 and an intercept of 10; in complete congruence with the Global Meteoric Water Line (GMWL) [Craig, 1961]. In more “normal” years, the LMWLs for these southern Australian locations always have lesser slopes (Mt. Donna Buang 6.4, Melbourne 7.1, Cape Grim 6.3) than the GMWL and more variable intercepts. Melbourne and Cape Grim sampling stations are at elevations close to sea level

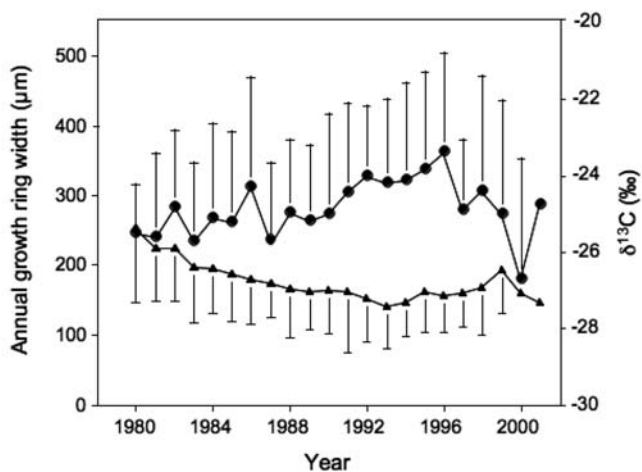


Figure 4. Annual variation in growth (closed circles) and carbon isotope discrimination (closed triangles) of *N. cunninghamii* growing at a range of altitudes and topographic locations on Mt. Donna Buang. Error bars are standard deviations from means.

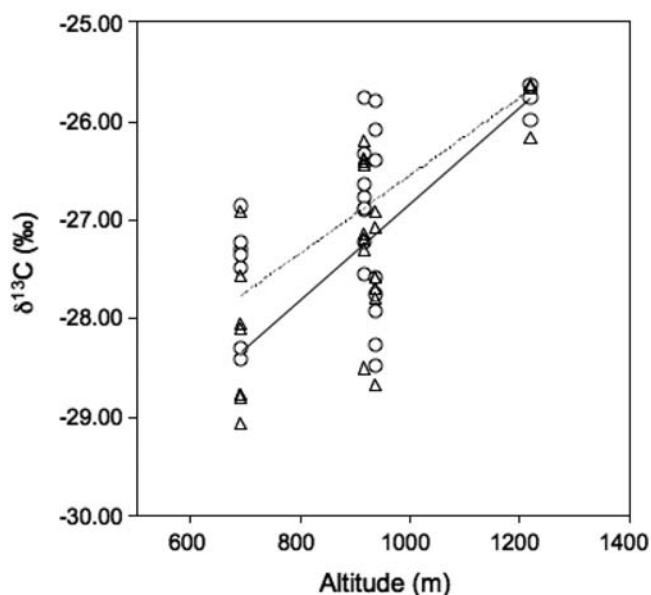


Figure 5. Altitudinal variation, in both wet (open triangles) and dry (open circles) years, in abundance of ^{13}C within latewood from tree rings ($n = 28$). Data are derived from cores of seven trees. Wood samples from the four wettest (1986, 1989, 1993, and 1996) and driest (1982, 1987, 1994, and 1997) years were selected from the 20 year record available in each core. Dotted line represents linear regression for the driest years ($y = 0.004x - 30.51$, $r^2 = 0.4$), and solid line represents linear regression for the wettest years ($y = 0.005x - 31.7$, $r^2 = 0.6$).

and are located within short distances of the coastline, while the Mt. Donna Buang samples were collected over a range of altitudes from 240 to 1250 m at locations around 70 km inland.

[26] The most likely cause of the year-on-year variation in the LMWL is prevailing climatic conditions, especially contributions to total rainfall from oceanic versus continental sources. The lesser (than GMWL) slopes of LMWL over long periods in southeastern Australia are probably due to contributions of continentally influenced rainfall (e.g., associated with northerly and northwesterly winds, carrying water vapor from inland Australia) [see Whetton, 1988; Nicholls, 1989]. Recently, Ummenhofer et al. [2009] reassessed causes of drought in southeast Australia on the basis of correlation of temperature data for the Indian Ocean with recorded and interpolated climatic conditions. They concluded that variability in Indian Ocean temperatures (an Indian Ocean Dipole) were a much more likely cause than the previously assumed variation in temperatures across the Pacific Ocean (the El Niño–La Niña phenomenon). Our data provide the first empirical and direct evidence of the different drought and nondrought contributions of rainwater from different origins to rainfall in southeastern Australia. The lack of nearly all continentally influenced rainwater during the drought of 2001 and 2002 ensured that LMWLs were nearly identical to the GMWL. As far as we can tell, this is the first time that continental effects on rainwater and stream water have been identified for small catchments in Australia.

[27] Stream water and rainwater samples were closely related in their ratios of $\delta^{18}\text{O}:\delta^2\text{H}$. All collected samples produced tightly clustered ratios that fell within the lower end of the range recorded for rainwater, suggesting that stream water was weighted toward origin from the higher, colder elevations of the Cement Creek catchment. Similarly, the rapid switch in ratio from November/December 2002 to February and thereafter in 2003 suggests short residence times for much of the water that falls within the catchment [Clark and Fritz, 1997]. This is supported by the near identical relation between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ for rainwater and stream water in each sampling period (November/December or February–September). The close relation between isotopic signatures of rainwater and stream water precludes delineation of the base flow component on the basis of isotope analysis [Stewart and McDonnell, 1991; Turner and Barnes, 1998].

[28] The $\delta^{18}\text{O}:\delta^2\text{H}$ signatures of soil water and twig water were bounded by the 2002 LMWL and the 2003 LMWL (Figure 3). In addition to a freely draining component of rainwater, a proportion is retained in soils for periods sufficient to produce evaporative enrichment, albeit with little change in $\delta^{18}\text{O}:\delta^2\text{H}$. Evaporative enrichment of soil water in these ecosystems can be attributed to the good structure of the gradational kraznozems in question, especially their strong ped structure that accompanies their high clay content [Ashton and Attiwill, 1999]. The good structure ensures the soils drain freely with little if any overland flow, yet retain significant amounts of water. The shared LMWL for rainwater and stream water is thus due to the sheltered southerly aspect, generally high rainfall, and steep slopes of the Cement Creek catchment. Moreover, the clear and consistent differences in isotopic composition of both rainwater and stream water (that share the same LMWLs) between 2002 and 2003 argues strongly that recent rainfall contributes the great majority of current streamflow.

[29] A depth of understanding of the effects of evaporative enrichment on isotope signatures of plant organic matter has developed quickly in recent years [Barbour, 2007; Barnard et al., 2007]. The importance of evaporative enrichment of the water isotopologues containing ^{18}O and ^2H in leaf water and the transfer of this isotope signal to assimilates has now been clarified [Roden and Ehleringer, 1999; Barbour and Farquhar, 2000; Farquhar and Gan, 2003; Gessler et al., 2007]. Our data support the need for simultaneous sampling and analysis of source water and plant tissues (foliage and wood) to fully interpret environmental influences from $\delta^{18}\text{O}$ signatures. This is particularly problematic for retrospective tree ring analysis where source water $\delta^{18}\text{O}$ is unobtainable. While there are sites and ecosystems where the GMWL may be used as a reasonable approximation of past LMWL, as shown here there are also ecosystems that display very considerable year-to-year variation in LMWL. Even if the $\delta^{18}\text{O}:\delta^2\text{H}$ relation of rainwater and soil water and twig water have similar slopes, as suggested by Figure 3, the offset (y intercept) may vary considerably, making difficult, if not impossible, accurate predictions of twig water $\delta^{18}\text{O}$ in the past, even when the LMWL may be known. We note that in many respects, our study sites are close to ideal for $\delta^{18}\text{O}$ studies inasmuch as there seems little evidence of water limitations of stomatal conductance. This serves to reinforce the view that variation

in source water $\delta^{18}\text{O}$ can confound efforts to interpret $\delta^{18}\text{O}$ in tree rings.

[30] Similar to the requirements for background isotopic data for water, our data highlight the importance of background variation in $\delta^{13}\text{C}$ of atmospheric CO_2 , especially when there is little influence of water availability on stomatal conductance. For example, summer rainfall was not a good predictor of $\delta^{13}\text{C}$ in foliage, in contrast to the relation reported by Read and Farquhar [1991]. The general pattern of $\delta^{13}\text{C}$ in both wood and foliage (Figure 4 and Table 2) suggests that stomata are playing a minor role in regulating water fluxes on the sites studied here. The overall small difference ($<1\text{‰}$) in isotopic composition of wood of *N. cunninghamii* supports recent research [Tausz et al., 2005] showing stomata remaining open with little variation, despite large variation in light and temperature regimes. Similarly, foliage $\delta^{13}\text{C}$ also varied $<1\text{‰}$ between trees growing literally within Cement Creek with an obvious permanent source of water and those growing up to 100 m distant from the creek.

[31] Many studies have reported declines in $\delta^{13}\text{C}$ in late wood over the past century. The global data set encompasses many species, including both *Fagus* [Duquesnay et al., 1998] and now *Nothofagus*. Altitude influences $\delta^{13}\text{C}$ through reduced partial pressure of atmospheric CO_2 (P_a) and thus internal CO_2 pressure (P_i). In addition, increasing elevation causes a reduction of O_2 partial pressure and an associated increase in assimilation rates [Körner et al., 1991]. Nonetheless, syntheses of the effects of altitude on P_i and $\delta^{13}\text{C}$ in trees [e.g., Körner et al., 1988; Hultine and Marshall, 2000; Warren et al., 2001] and specific studies of effects of altitude on stomatal conductance of *N. cunninghamii* [Hovenden and Brodribb, 2000] suggest that the difference between external and internal concentrations of CO_2 ($P_a - P_i$) is conserved over a considerable range of altitudes. This is consistent with an interpretation that stomatal conductance of *N. cunninghamii* only weakly responds to daily, monthly, or seasonal fluctuations in water availability but is adapted in the long term to maintain more or less constant internal partial pressures of CO_2 . The change in $\delta^{13}\text{C}$ of atmospheric CO_2 over the past century (the Suess effect), especially the last 20 years, is thus a dominant component of the change in δ recorded in tree rings at Mt. Donna Buang.

[32] The growth data recorded in tree rings for *N. cunninghamii* support generalizations made by Cunningham and Read [2002] that Australian temperate rain forest species may be better able to maintain maximum net photosynthesis over a range of growth temperatures than their tropical counterparts. We found that growth was better closer to the summit (1000+ m) than at any other altitude (Table 3) in contrast to the more general expectation that photosynthesis and growth might be better at the higher mean annual temperatures found at lower and more sheltered locations. Even in the driest years, rainfall at the summit of Mt. Donna Buang seldom falls below 1200 mm annually or 70 mm monthly. Accordingly, nothing in our data supports a strong role of water availability in growth or distribution or patterns of water use of *N. cunninghamii* within the broad region of study.

[33] Meteoric water varied significantly in isotope composition from year to year at Mt. Donna Buang and at other

long-term monitoring sites in southeast Australia. We conclude the variation is due to the variable contributions to total rainfall of that originating from (1) the north (with a consequently large continental effect) and (2) the south (with no continental effect), relative to sampling sites. Such variations pose considerable challenges for the use of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ signatures to trace sources of water currently used by trees and the effects of past climates on tree growth and physiological performance (via tree ring analysis). Our study highlighted large variation in $\delta^{13}\text{C}$ between individual trees growing in native forests on steep slopes, where light varies greatly. The use of isotopic data for inferring the future impacts of climate change on hydrology of native forests clearly requires caveats. Our data suggest hydrological modeling can be simplified for steeply sloping, southerly facing catchments dominated by eucalypt-*Nothofagus* stands, since tree water use is not strongly coupled to climatic conditions (via stomatal conductance).

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