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Can oxygen stable isotopes be used to track precipitation moisture source in vascular plant-dominated peatlands?

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ABSTRACT

Variations in the isotopic composition of precipitation are determined by fractionation processes which occur during temperature- and humidity-dependent phase changes associated with evaporation and condensation. Oxygen stable isotope ratios have therefore been frequently used as a source of palaeoclimate data from a variety of proxy archives, which integrate this signal over time. Applications from ombrotrophic peatlands, where the source water used in cellulose synthesis is derived solely from precipitation, have been mostly limited to Northern Hemisphere *Sphagnum*-dominated bogs, with few in the Southern Hemisphere or in peatlands dominated by vascular plants. New Zealand (NZ) provides an ideal location to undertake empirical research into oxygen isotope fractionation in vascular peatlands because single taxon analysis can be easily carried out, in particular using the preserved root matrix of the restionaceous wire rush (*Empodisma* spp.) that forms deep Holocene peat deposits throughout the country. Furthermore, large gradients are observed in the mean isotopic composition of precipitation across NZ, caused primarily by the relative influence of different climate modes. Here, we test whether δ^{18}O of *Empodisma* α-cellulose from ombrotrophic restiad peatlands in NZ can provide a methodology for developing palaeoclimate records of past precipitation δ^{18}O. Surface plant, water and precipitation samples were taken over spatial (six sites spanning >10° latitude) and temporal (monthly measurements over one year) gradients. A link between the isotopic composition of root-associated water, the most likely source water for plant growth, and precipitation in both datasets was found. Back-trajectory modelling of precipitation moisture source for rain days prior to sampling showed clear seasonality in the temporal data that was reflected in root-associated water. The link between source water and plant cellulose was less clear, although mechanistic modelling predicted mean cellulose values within published error margins for both datasets. Improved physiological understanding and modelling of δ^{18}O in restiad peatlands should enable use of this approach as a new source of palaeoclimate data to reconstruct changes in past atmospheric circulation.

1. Introduction

Variations in the stable isotopic composition of precipitation (δ^{18}O and δD) are determined by multiple fractionation processes which occur during temperature- and humidity-dependent phase changes associated with evaporation and condensation (Dansgaard, 1964; Craig and Gordon, 1965; Gat, 2000). The isotopic composition of precipitation is also known to reflect rainout history and atmospheric circulation patterns along given air mass trajectories (Cole et al., 1999; Araguas-Araguas et al., 2000). The subsequent incorporation of this signal into plants, sediments and ice has led to the use of oxygen stable isotope ratios (δ^{18}O) for palaeoclimate reconstructions from a variety of proxy archives including tree rings, lakes, speleothems (see Leng, 2004 and references therein), ice cores (Brook, 2007) and, less frequently, in peatlands. Ex-

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ploitation of the $\delta^{18}O$ record from ombrotrophic peatlands, where the source water used in cellulose synthesis is derived solely from precipitation, has been mostly limited to Northern Hemisphere *Sphagnum*-dominated bogs (e.g. Brenninkmeijer et al., 1982; Ménot-Combes et al., 2002; Zanazzi and Mora, 2005; Daley et al., 2010). There has been limited application in the Southern Hemisphere (SH; Royles et al., 2013) or in vascular plant-dominated peatlands (Hong et al., 2000, 2009), despite considerable potential for such records to improve understanding of SH climate dynamics.

The oxygen stable isotope content of vascular plant cellulose ($\delta^{18}O_C$) is determined by kinetic and equilibrium fractionation pathways from source water (Barbour, 2007). Leaf water is used for sucrose synthesis in plants and is generally isotopically enriched relative to meteoric source water ($\delta^{18}O_{SW}$) due to evaporative enrichment during transpiration (Yakir and DeNiro, 1990; Buhay et al., 1996). $\delta^{18}O_C$ depends on both the isotopic composition of the sucrose and that of the water at the site of cellulose synthesis, which may be spatially and temporally separated from sucrose synthesis. Models to describe these fractionation processes and predict $\delta^{18}O_C$ from $\delta^{18}O_{SW}$ have been developed, initially for trees (e.g. Waterhouse et al., 2002), but have been widely applied, including to peatlands dominated by different vegetation types (e.g. Ménot-Combes et al., 2002; Zanazzi and Mora, 2005; Daley et al., 2010). Vascular and non-vascular plants record different $\delta^{18}O$ from a given water source (Ménot-Combes et al., 2002; Nichols et al., 2010), largely due to the presence/absence respectively of stomata capable of regulating moisture/gas exchange. In addition, although $\delta^{18}O_C$ records have previously been interpreted as 'palaeo-thermometers' driven by surface air temperature (e.g. Hong et al., 2000), this link is indirect (Barbour, 2007), can be complicated by the uncoupling of air and leaf temperatures (Helliker and Richter, 2008) and is often untested (e.g. Oldfield, 2001). Quantitative palaeo-temperature estimates from peatland $\delta^{18}O_C$ data are therefore problematic and instead, $\delta^{18}O_C$ has been interpreted as a proxy for precipitation moisture source (Daley et al., 2010). If palaeoclimate indices are developed from $\delta^{18}O_C$ records in novel geographical or ecological contexts, it is critical that relationships between the isotopic compositions of precipitation, source waters and plant cellulose are empirically and mechanistically grounded and calibrated with modern climate data (e.g. Daley et al., 2012), or understood via probabilistic statistical approaches such as inverse proxy modelling (Yu et al., 2011; Yu, 2013).

The primary influences on the stable oxygen isotopic composition of plant cellulose are 1) the isotopic composition of source water and of water at the site of cellulose synthesis; 2) isotopic enrichment of water in the leaf due to evaporation (i.e. equilibrium and kinetic physical fractionation effects); and 3) biochemical fractionations during cellulose synthesis. Whilst physical fractionation effects are temperature- and humidity-dependent, the biochemical fractionation of $27 \pm 3‰$ (Yakir and DeNiro, 1990; Aucour et al., 1996) has generally been considered to be independent of temperature, although some evidence exists to the contrary (Sternberg and Ellsworth, 2011). In studies of $\delta^{18}O_C$ from *Sphagnum*-dominated peatlands, physical fractionation processes have been disregarded due to the simpler physiological water-use strategies of mosses compared to vascular plants, such that only a biochemical fractionation factor has been applied to test the link between moss cellulose and $\delta^{18}O_{SW}$ (Daley et al., 2010).

Throughout NZ, ombrotrophic peatlands are dominated by the restionaceous wire rush (*Empodisma minus* and *Empodisma robustum*; Wagstaff and Clarkson, 2012). Both species, occurring separately north and south of 38°S (known as the 'Kauri Line'), have reduced, scale-like leaves, high water-use efficiency, a surface cluster root matrix with a similar base exchange and water holding capacity to *Sphagnum*, can reduce water loss via stomatal control and form a dense canopy of standing living and dead shoots, reducing rates of surface evaporation (Agnew et al., 1993; Campbell and Williamson, 1997; Wagstaff and Clarkson, 2012). NZ is therefore an ideal location to develop understanding of oxygen isotope fractionation in vascular plant peatlands because the dominance of a single taxon in both surface vegetation and peat avoids mixed species effects (Ménot-Combes et al., 2002; Nichols et al., 2010). Many of the peatlands also preserve high-resolution full-Holocene sequences (e.g. Newnham et al., 1995; Vandergoes et al., 2005) and are situated in the climatically sensitive SH mid-latitudes (e.g. Ummenhofer and England, 2007; Fletcher and Moreno, 2012). Crucially, large gradients exist in the annual mean isotopic composition of precipitation across NZ (Fig. 1), caused primarily by the relative influence of northern and southern air masses driven by different climate modes (e.g. ENSO and the southern westerlies, driven by the Southern Annular Mode; Ummenhofer and England, 2007), as well as altitude and rainout effects across inland areas.

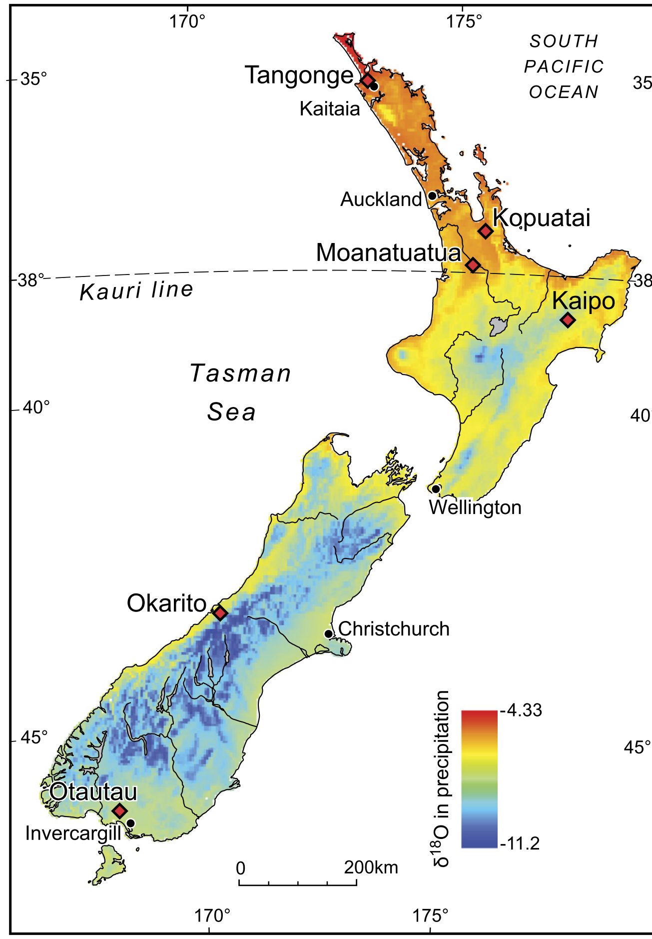

Fig. 1. Site locations. Kauri line represents geographical split of the two *Empodisma* species *E. robustum* (to the north of 38°) and *E. minus* (to the south of 38°) (Wagstaff and Clarkson, 2012). Base map is isoscape modelled annually-weighted 1997–2013 mean $\delta^{18}O$ in precipitation (‰; see Section 2.2 for details) generated using the relationships reported in Table S1. For a full colour version of this figure, the reader is referred to the web version of this article.

Here, we test the potential for $\delta^{18}O$ in ombrotrophic restiad peatlands to provide a basis for developing palaeoclimatic records that track precipitation moisture source. Specifically, we test the following hypotheses:

H1: The oxygen stable isotopic composition of the source water ($\delta^{18}O_{SW}$) used by *Empodisma* spp. in cellulose synthesis tracks the isotopic composition of precipitation, both spatially and temporally.