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Disclosing biome sensitivity to atmospheric changes: Stable C isotope ecophysiological dependences during photosynthetic CO_2 uptake in Maritime pine and Scots pine ecosystems from southwestern Europe

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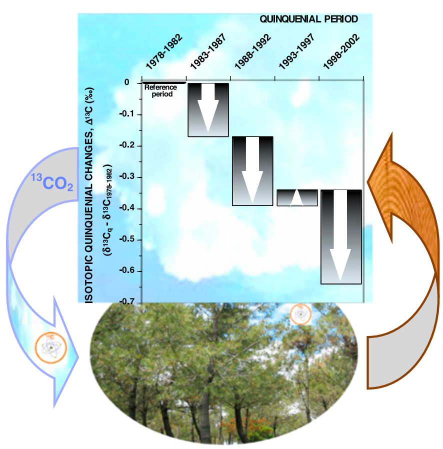
HIGHLIGHTS

- Novel approach can smooth individual variability in tree-ring C isotopic records.
- Compared to Maritime pine, Scots pine wood is significantly ^{13}C enriched.
- Pine forest stand quality affects the tree-ring C isotope composition.
- Tree-ring δ^{13}C can reflect the biome sensitivity to atmospheric changes.
- Nuanced responses of the biosphere to global change shown by isotopic dendrology.

GRAPHICAL ABSTRACT



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ABSTRACT

Background: The late XX century showed a sharp atmospheric $\delta^{13}CO_2$ decline mainly ascribed to increased emissions of greenhouse gases (GHG) resulting from fossil fuel combustion. Thus, in the current global-warming scenario, a deep knowledge of biosphere–atmosphere interactions became especially relevant to adopt appropriate guidelines for climate change management.
Objective: Although tree-rings can attest long-term atmospheric composition trends, C isotopic variability among individual trees often disturbs the accurate interpretation of ^{13}C atmospheric changes from tree-rings at different timescales. Therefore, the aim of this research is to overcome this intertree variability by applying an isotopic approach that can practically absorb high-frequency climatic irregularities and genetic variabilities from dendrochronological series, hence allowing the accurate deconvolution of past atmospheric composition to improve current models.
Methods: This research is based on original isotopic dendrochronological results obtained by performing tree-by-tree differential studies with intra-tree δ^{13}C shifts to allow interspecies data standardization.
Results: The isotopic composition of dendrochronological series collected from northwestern Spanish coniferous ecosystems clearly reflected the corresponding atmospheric ^{13}C changes but the stringency of the match also depended on some silvicultural parameters, tree-ring isotopic composition being able to exhibit either a magnification or attenuation of atmospheric changes according to specific metabolic differences that modulate photosynthetic ^{13}C discrimination in each ecological context.

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Conclusion: Relative isotopic changes revealed from our 25-year-long dendrological research, which properly mirrored the contemporary atmospheric $^{13}CO_2$ composition (1978–2002), also showed the biome sensitivity to atmospheric changes, pointing towards a notable aptitude to respond to even incipient mitigation strategies and a significant resilience capacity of the Earth system.

1. Introduction

Stable carbon isotope concentration in the Earth's atmosphere is the result of a continuous balance between both CO_2 emission and CO_2 uptake from biological, physical and anthropogenic processes in every ecosystem, isotopic monitorization being in recent times extensively used to trace the global C cycle (Ghosh and Brand, 2003; Pawelczyk and Pazdur, 2004; Pazdur et al., 2007; Zhao et al., 2006). Over the last 200 years, worldwide industrial development (including petroleum combustion), deforestation, wildfires and agricultural transformations (Cabaneiro et al., 2008; Fernandez et al., 1999, 2012a,b) among others, altered this balance leading to progressive increases of atmospheric CO_2 levels and substantial $\delta^{13}CO_2$ decreases (1.5‰) according to recent $\delta^{13}C_{atmosphere}$ records (Keeling et al., 2010).

It is well known that predictable ^{13}C discrimination occurs in photosynthesis (Körner et al., 1991; Lai et al., 2004; Suits et al., 2005) caused not only by differences between $^{13}CO_2/^{12}CO_2$ stomatal diffusion rates but mainly by kinetic differences of enzymatic reactions involved on their biochemical fixation (Ghosh and Brand, 2003). Consequently, net fractionation by C3-photosynthesis can be quantified using a binomial equation having diffusion-dependent and biochemistry-dependent terms (Farquhar et al., 1982), as long as we start from reliable plant isotopic information, meaning that C isotopes in dendrochronological series from C3 arboreal vegetation can be powerful tools for remote atmospheric reconstruction (Feng and Epstein, 1995; McCarroll and Loader, 2004; McCarroll et al., 2009; Pawelczyk and Pazdur, 2004; Pazdur et al., 2007; Zhao et al., 2006). On the other hand, the natural isotopic variability among individual trees, even growing under similar conditions (Brendel et al., 2002; Fernandez et al., 2005; Körner et al., 1991; Torn et al., 2011), joined to the inherent randomness of environmental fluctuations, often frustrates the accurate dendrochronological interpretation of atmospheric $\delta^{13}C$ changes at different timescales. That is why this approach was disused in the 1980s when air trapped in polar ice cores was considered more reliable for reconstruction past atmospheric composition and when it became better appreciated that tree-ring C isotopes were impacted by many factors besides atmospheric composition (Diefendorf et al., 2010; Feng, 1999; Saurer et al., 2004; Szczepanek et al., 2006), especially those linked to the tree water-use efficiency which in turn depends on other parameters such as meteorological restrictions, underlying soils characteristics, plant root conditions, etc. (Klein et al., 2012; Mutabaruka et al., 2002). However, in very recent times, the renewed use of isotopic mass spectrometry in combination with the classical dendrochronology is steadily increasing (Sidorova et al., 2012). Nowadays, many authors consider not only that stable isotope ratios, particularly $^{13}C/^{12}C$ (or $^{18}O/^{16}O$) in wood or cellulose, provide complementary information about climatic variabilities but also that growing tree-rings are unique in their ability to provide high-resolution, absolutely dated atmospheric signals for the study of palaeoclimatology (Heinrich et al., 2013). As a consequence of this contemporary expanding number of research works that consider this renewed isotopic approach, there is a parallel growing interest in the application of advanced statistical techniques to model not only plant physiological adaptation to the global rise in the atmospheric CO_2 concentration (De Boer et al., 2011), but also the influence of different environmental variables in plant carbon isotope discrimination (Leonardi et al., 2012)

Therefore, the immediate objective of this research is to link the ^{13}C content of growing tree-rings formed during a specific time interval with the direct contemporary air $\delta^{13}CO_2$ determinations at an infra-decadal resolution and to circumvent any possible high-frequency oscillating external factor that may mask the straight relationship between biome C uptake and atmospheric composition. The work hypothesis is that methodological approaches able to absorb meteorological and individual variability affecting growing-ring isotopes will improve current ^{13}C dendrochronology resolution. The ultimate aim of this research is to study the ecosystem sensitivity to atmospheric changes and to overcome any ecological/physiological interference that could distort the relationship between atmospheric and tree-ring isotopic compositions, boosting the dendrochronological potential of C3-wood to scrutinize atmospheric changes for remote or recent periods. The proposed updating would also contribute to understand terrestrial C cycle mechanisms as well as Earth's resilience capacity against human impacts, helping to infer the likely biosphere reactions to future cutbacks of total GHG's emissions in order to establish better strategies for smoothing climate changes.

2. Materials and methods

2.1. Experimental design

All forests selected to obtain dendrochronological series were scattered between 42°01′22.2″–43°12′27.2″ N and between 6°59′41.1″–8°51′25.8″ W in the Northwest of Spain (temperate-humid climate zone) and located at different altitudes (from 256 to 1378 m above sea level) in order to include a fair representation of different local ecological factors. Twenty different pure coniferous plantations of either Maritime pine (*Pinus pinaster* Ait.) or Scots pine (*Pinus sylvestris* L.) were chosen to represent the whole range of tree densities, undergrowth types and growing conditions in Galician pine forests (Fig. 1). The group of forests selected, even-aged stands with trees older than 25 years (10 Maritime pine plantations and 10 Scots pine plantations), comprised an equal number of plots for each forest stand quality considered (10 stands of low quality and 10 stands of high quality). The forest stand quality index used (site index: S.I.) is defined as the height of dominant trees (in metres) at the age of 20 years for Maritime pine (Álvarez González et al., 2005) and at the age of 40 years for Scots pine (Diéguez-Aranda et al., 2005). To allow the comparison of forest plantations with different pine species, standardized site index values "S.I. (%)", which assign a percentual numerical figure to the quality of the stand, were calculated by using an extensive number of plantations that encompassed the whole quality range of each one of these types of pine forests in northwestern Spain (Álvarez González et al., 2005; Diéguez-Aranda et al., 2005).