Tropical dendrochemistry: A novel approach to estimate age and growth from ringless trees

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[1] Although tropical forests play an active role in the global carbon cycle and climate, their growth history remains poorly characterized compared to other ecosystems on the planet. Trees are prime candidates for the extraction of paleoclimate archives as they can be probed sub-annually, are widely distributed and can live for over 1400 years [*Chambers et al.*, 1998]. However, dendrochronological techniques have found limited applications in the tropics because trees often lack visible growth rings (Whitmore, 1990). Alternative methods exist (dendrometry (DaSilva et al., 2002), radio- and stable isotopes (Evans and Schrag, 2004; Poussart et al., 2004; Poussart and Schrag, 2005), but the derived records are either of short-duration, lack seasonal resolution or are prohibitively labor intensive to produce. Here, we show the first X-ray microprobe synchrotron record of calcium (Ca) from a ringless *Miliusa velutina* tree from Thailand and use it to estimate the tree's age and growth history. The Ca age model agrees within ≤2 years of bomb-radiocarbon age estimates and confirms that the cycles are seasonal. The amplitude of the Ca annual cycle is correlated significantly with growth and annual Ca maxima correlate with the amount of dry season rainfall. Synchrotron measurements are fast and producing sufficient numbers of replicated multi-century tropical dendrochemical climate records now seems analytically feasible. **Citation:** Poussart, P. M., S. C. B. Myneni, and A. Lanzirotti (2006), Tropical dendrochemistry: A novel approach to estimate age and growth from ringless trees, *Geophys. Res. Lett.*, *33*, L17711, doi:10.1029/2006GL026929.

1. Introduction

[2] Recent studies indicate that tropical forests worldwide are highly sensitive to extreme events like El Niño and to deforestation-driven reductions in rainfall [*Trenberth and Hoar*, 1997]. Although a number of proxies exist for reconstructing tropical climate (corals, ice cores, speleothems and varved sediments), there remains a shortage of sub-annually resolved proxies from terrestrial environments, which are key for understanding climate and carbon cycling dynamics. Because trees are widely distributed in the tropics, often grow throughout the year and can be long lived, they may be used as proxies for reconstructing multi-century climate records from the terrestrial tropics. However, dendrochronology studies based on ring counting are few in the tropics [*Whitmore*, 1990] (Figure 1), although selected species are appropriate for tree ring analysis [*Fahn et al.*, 1981]. The general absence of anatomically distinct annual growth rings, discontinuous banding and false rings in many tropical tree species make accurate age-modelling difficult [*Stahle*, 1999]. Radiocarbon (^{14}C) measurements can be used to assess the annual nature of growth rings [*Biondi and Fessenden*, 1999] and estimate the age and average growth rates of tropical trees [*Poussart et al.*, 2004; *Poussart and Schrag*, 2005]. However, uncertainties associated with soil respiration, internal carbohydrate transfer and species-specific effects can limit the application of ^{14}C dating [*Worbes and Junk*, 1989]. Alternatively, dendrometer bands [*DaSilva et al.*, 2002], repeated diameter measurements [*Lieberman and Lieberman*, 1987] and cambium wounding methods [*Mariaux*, 1967] may be used although their application is restricted to the last couple of decades. Analysis of tropical wood chemistry may bare seasonal signatures of cambium activity. Studies in Indonesia [*Poussart et al.*, 2004] and Thailand [*Poussart and Schrag*, 2005] (Figure 1) demonstrate that the generation of replicated sub-annual $\delta^{18}O$ and $\delta^{13}C$ records from ringless tropical trees is possible over several decades. However, because hydrological patterns are spatially heterogeneous, large sample sets are required to capture climatically robust signals. Cellulose sample preparation remains labour intensive and record replication is challenging. Here, we show how seasonally resolved trace element records measured on tropical ringless trees, like temperate forest tree ring records, can serve as proxies for dating and reconstructing growth and climate histories. The technique relies on synchrotron X-ray microanalysis and allows more versatility in sample state, including analyses of liquid and hydrated solids such as wood. The analysis can be done in air without a requirement for sample pre-treatment or coating. Using this approach, large numbers of dendrochemical records can be generated and replicated rapidly helping to fill a critical gap in climate time series from the terrestrial tropics.

[3] Trees uptake trace elements via their roots, foliage and bark [*Clarkson*, 1984]. The fluxes of trace elements are regulated by their bioavailability within the soil matrix as well as their particular metabolic function during growth [*Martin et al.*, 2003]. Elements distribution in the xylem varies according to external factors such as climate and site specific characteristics and internal factors such as tree age, pathway dependent delivery time between uptake and incorporation, heartwood/sapwood (H/S) transfer and wood density [*Watmough*, 1997].

[4] A number of dendrochemical studies report historical changes in soil and atmospheric chemistry as well as climate [*Watmough*, 1997]. However, a mechanistic framework for the incorporation of trace elements into trees remains largely incomplete. Observation of radial mobility

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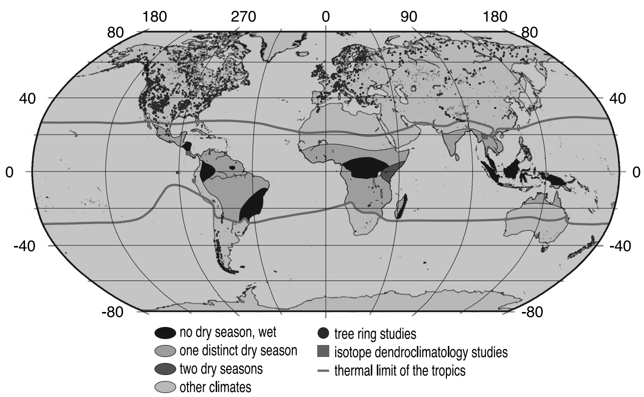

Figure 1. Global map showing the distribution of tree ring studies (circles) as compiled by the World Data Center for Paleoclimatology as of January 2005 (Map created using *i*GMT [*Becker and Braun*, 1998]). Squares represent the location of tropical isotope dendroclimatology studies in Costa Rica and Peru [*Evans and Schrag*, 2004] and in Indonesia and Thailand [*Poussart et al.*, 2004; *Poussart and Schrag*, 2005]. Rainfall seasonality in the tropics is derived from climate diagrams from *Walter and Lieth* [1967] and *Worbes* [1995].

of certain elements [*Martin et al.*, 2003; *Nabais et al.*, 2001], the existence of species-specific pith-to-cambium concentration gradients along with differences in H/S physiology render some records difficult to interpret. Consequently, recent temperate latitude studies are carefully evaluating such factors and converging on selected species and elements with low radial mobility such as Ca and Zn [*Nabais et al.*, 2001].

2. Methods

[5] Recent innovations in analytical techniques are enabling the measurement of multiple elements directly on whole wood samples with minimal sample preparation, low detection limits and μm-scale resolution [*Watmough*, 1997]. Studies on temperate trees with annual growth rings report seasonal variations of trace elements using synchrotron radiation induced X-ray emission [*Martin et al.*, 2001], secondary ion mass spectrometry [*Brabander et al.*, 1999; *Martin et al.*, 1998] and proton induced X-ray emission spectrometry [*Harju et al.*, 1996]. To date, there are no published records showing seasonally-resolved trace element variations from tropical ringless trees.

[6] We collected a *Miliusa velutina* sample (PK1) from the Annonaceae family in the forest of Pangmapa (98°16′E, 19°34′N), northern Thailand (Figure 1). This deciduous species is common to semi-open forests and grows between 5–16 m in height. The sample was felled around the year 2000. The region undergoes three distinct seasons: cool and dry (November to February), hot and dry (March to May) and warm and wet (May to October). We measured radial trace element records on PK1 at the Brookhaven National Synchrotron Light Source Facility and found the first evidence for a tree with no visible growth rings to retain records of seasonality. The relative distribution of major and trace elements in tree cores was examined directly using focused synchrotron X-ray beams (4–5 micron spot size) at beamline X26A National Synchrotron Light Source. The sample was excited using high-energy monochromatic X-rays of energy 10–12 keV, and the X-ray emission spectra were collected and analyzed using a 9-element Ge array detector. We collected 2 line scans (at a resolution of 15 and 100 μm between each point), with a few millimetres between the two line scans. The records were replicates of each other. We also prepared a uniformly thick horizontal section of 4 mm to minimize the thickness dependent variations in elemental concentration. The technique involves minimal sample preparation and the time required for the measurement is short (~1 hr/cm, depending on detection sensitivity).

3. Results and Discussion

3.1. Hearthwood Versus Sapwood Distributions

[7] Calcium is the most abundant and least mobile of the trace elements analyzed in this tree (Zn, Cu, Fe, K, Mn and Ni) by at least a factor of 2, which is consistent with previous findings [*McLaughlin and Wimmer*, 1999]. The H/S boundary often coincides with an increase in the content of trace elements [*Okada et al.*, 1990]. As shown for Ca in Figures 2a and 2b, the visible H/S boundary corresponds to a twofold increase in Ca intensity (concentration differences may be larger because of X-ray absorption effects). Such increase in Ca has also been observed by others who argued for a translocation of nutrients from the heartwood to the functional sapwood [*Okada et al.*, 1990; *Andrews et al.*, 1999]. The H/S boundary is also distinct for Cu and Zn where intensities decrease sharply toward the pith (data not shown).

3.2. Ca Seasonality

[8] The Ca (Figure 2b) and Zn (data not shown) records reveal distinct cycles from the cambium to the pith of the tree. A comparison with the $\delta^{18}O$ and $\delta^{13}C$ records [*Poussart and Schrag*, 2005] is shown in Figure 2c. Isotopic cycles are defined on average by 8 individual measurements whereas the Ca cycles have about 110 individual measurements. The difference in spatial resolution most likely accounts for the observed differences in timing of minima and maxima between the two sets of records. We construct an age model from the Ca record based on the assumption that the cycles have seasonal timescales and estimate that the tree dates back to 1909. When compared to bomb age estimates, we find that the two age models agree within $\leq$2 years and confirm that the Ca cycles are produced seasonally (Figure 3a). Our results represent the first time such cycles are observed in a tree with no visible growth rings and their origin remains to be determined. The work of [*Gourlay*, 1995] reports on the occurrence of crystalline calcium oxalate in marginal parenchyma of African *Acacia* species, delineating annual growth rings. The chemical form and site of residence of the calcium in PK1 is currently being investigated through detailed anatomical work and X-ray and infrared spectroscopy. Inspection of the sample's surface using a microscope reveals no visible changes in wood density. However, density effects on distribution need to be investigated further using the transmitted and incident X-ray intensities [*Punshon et al.*, 2005].

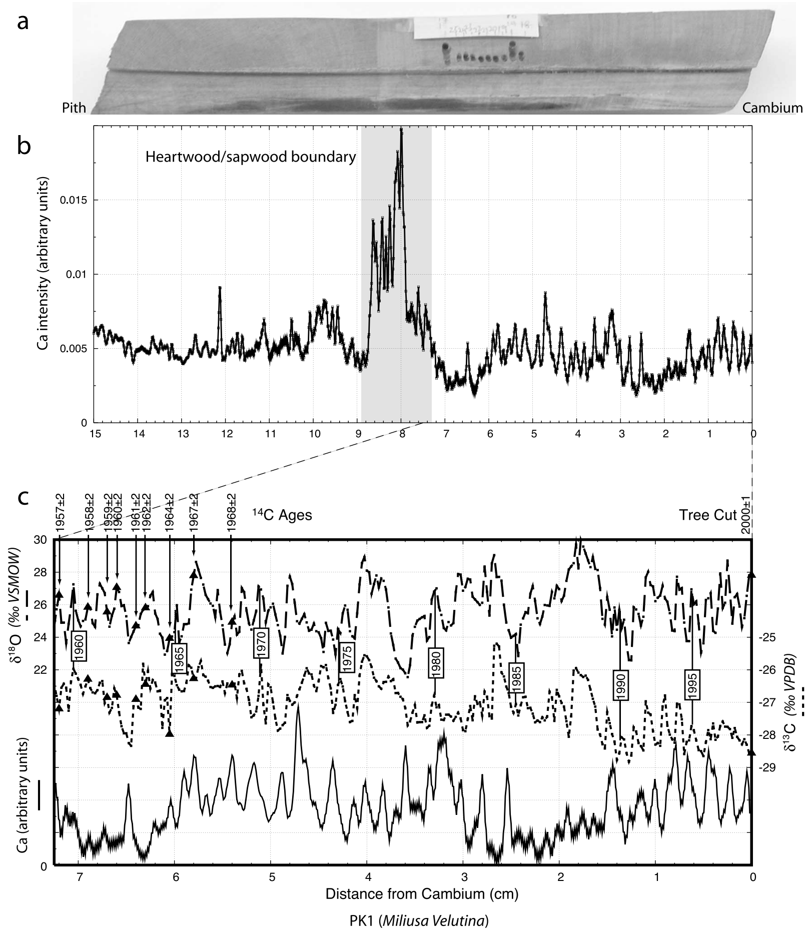

Figure 2. (a) Photograph of radial transect of *Miliusa velutina* sample (PK1) from Pangmapa, northern Thailand, showing a distinct heartwood/sapwood (H/S) boundary. (b) Synchrotron radiation line scan of Ca distribution (at a resolution of 100 μm and normalized to incident X-ray intensity) on PK1 showing a twofold increase in Ca intensity at the H/S boundary. Seasonal-like cycles are observed from the cambium to the pith. (c) Comparison of the $\delta^{18}O$ (long dashed line), $\delta^{13}C$ (short dashed line) [*Poussart and Schrag*, 2005] and Ca (solid line) records as a function of distance (cm) from cambium for PK1. The agreement between radiocarbon and stable isotope chronologies is within ≤2 years.

[9] All plant cell walls bind Ca, providing structure and rigidity to the cells [*Martin et al.*, 2001]. The main Ca target appears to be the pectic component. If greater amounts of pectin were being synthesized and secreted some time during the growing season, then seasonal Ca fluctuations may get recorded in the stem. Alternatively, the Ca cycles may be generated from an external forcing. In seasonal tropical forests, where leaf decomposition is synchronized to the annual dry season [*Cornejo et al.*, 1994], a pulsed release of Ca from decaying leaves and subsequent uptake by roots might also lead to a pulsed deposition in the growing woody tissue once each year [*Yavitt et al.*, 2004]. The effects of forest fires on Ca availability in soils [*Guyette and Cutter*, 1997] along with the non-metabolic controls of Ca uptake in trees via the transpiration stream [*Guyette*, 1994] could be potentially important processes in the cycling of nutrients in seasonally dry tropical forests and beckon further investigation.

3.3. Growth Estimates

[10] We estimate annual growth rates based on the distance covered between two adjacent minima. Growth estimates display significant interannual variability and average around 0.17 cm/year (Figure 3a), which agrees with previous estimates derived from a $\delta^{18}O$ chronology [*Poussart and Schrag*, 2005]. Growth uncertainties related to circumferential variability and reproducibility between trees growing in the same environment will be assessed in future studies. Work is currently underway to determine the timing of the trace element maxima and minima, which will assist in uncovering trace element incorporation mechanisms. The H/S boundary marks a transition in the Ca record where the mean amplitude of the Ca variations is 1.5 times greater on the cambium side relative to the pith side (Figure 2b). We find a significant correlation between estimated growth rates and the amplitude of the Ca seasonal cycle (r^2 = 0.65, $p < 0.01$) (Figure 3b) and no significant correlations between growth rates and Ca maxima and minima. Currently, few annual growth records from the tropics are longer than a couple of decades. The generation of tree growth time series extending beyond the observational record will help to quantitatively study the tropical carbon cycle and gauge CO_2 fertilization effects following the onset of the Industrial Revolution.

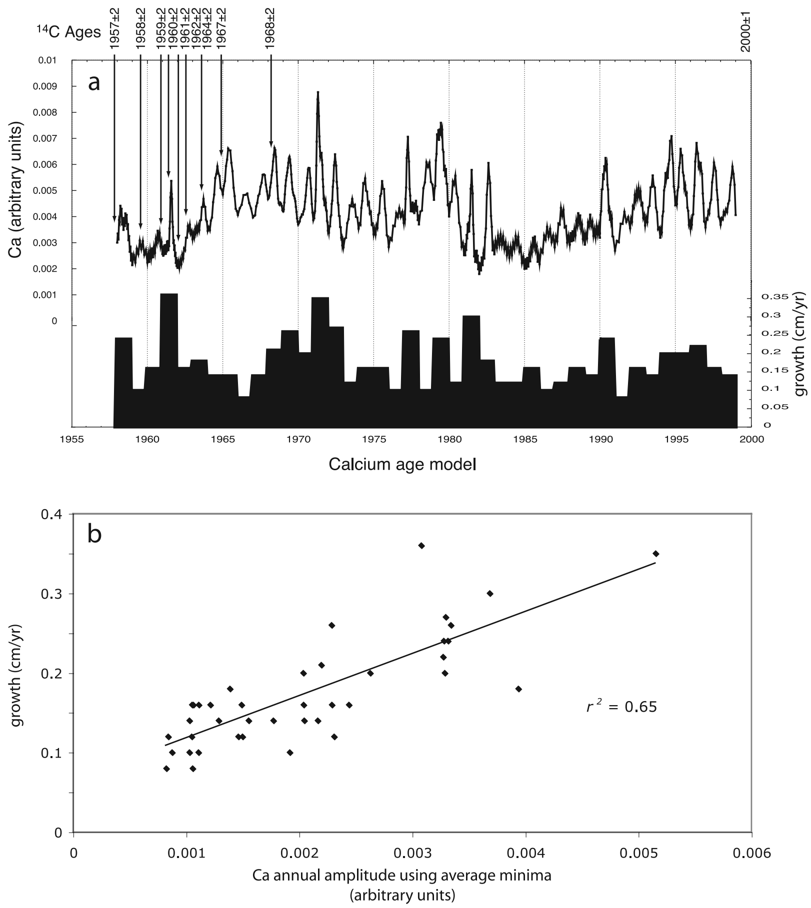

Figure 3. (a) Calcium age model for *Miliusa velutina* sample (PK1) from Pangmapa, northern Thailand. The radiocarbon and Ca chronologies agree to within ≤2 years and confirm a seasonal timescale of formation. Growth rate estimates based on Ca age model (cm yr^{-1}). (b) Correlation plot between estimated growth (cm yr^{-1}) and amplitude of Ca based on averaged annual minima ($r^2 = 0.65$, $p < 0.01$).

3.4. Ca and Rainfall

[11] The longest monthly rainfall data records from monsoonal northern Thailand extend back to 1950 for weather stations in Mae Hong Son, Chiang Mai and Mae Sariang. We find that annual maximum Ca intensities are significantly correlated with the amount of rainfall in March in Mae Sariang corresponding to the end of the dry season ($r = 0.47$, $p = 0.01$). The data documents the first record to show correlations between a trace element dendrochemical signal and rainfall seasonality and outlines the potential for paleoclimate applications.

4. Summary and Concluding Remarks

[12] Tropical dendrochemistry circumvents the need for visible growth rings, which are rare in the tropics, to reconstruct tree age and growth rate history. The approach uses synchrotron technology to measure multiple elements simultaneously on whole wood samples with minimal sample preparation and machine time, low detection limits and μm-scale resolution. The data presented here documents the first record to show trace element seasonal variations on a ringless tropical tree. The measured Ca cycles yield annual growth estimates in agreement with a previous study [*Poussart and Schrag*, 2005] using stable isotopes and suggest that the tree dates back to 1909. Efforts to reproduce such records using benchtop scanning XRF are underway and promise to broaden the applicability of this approach. While a physiological mechanism for the seasonal incorporation of Ca remains to be determined, we find a significant correlation between maximum Ca intensities and dry season monsoon rainfall, suggesting a link between Ca intensities and sub-annual variability in rainfall. It is only through extensive signal replication within and across trees that growth records may be cross-dated and statistically robust climatic information derived, as has been demonstrated in tree ring research. Because the synchrotron technique is so time-efficient, it is now analytically feasible to generate a large number of multi-elemental records. Future studies in tropical dendrochemistry hold the potential to provide seasonally resolved multi-century El Niño and Southeast Asian monsoon records, helping to fill a critical gap in the terrestrial tropics.

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