Central Vietnam climate over the past five centuries from cypress tree rings

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Abstract

We present the first crossdated tree ring record from central Vietnam, derived from the growth rings of the rare cypress *Fokienia hodginsii* from the mountains of Quang Nam Province near the Laos border. The Quang Nam *Fokienia hodginsii* time series (QNFH), based on the crossdated sequences of 71 increment core samples from 37 mature trees, is the third published dendrochronological record from this species. The record extends 667 years from AD 1347 to 2013 and exhibits a mean series intercorrelation of 0.526, similarly significant with the first two published *Fokienia hodginsii* records: 0.474 for Mu Cang Chai (MCFH) and 0.578 for Bidoup - Nui Ba National Park (BDFH) in the north and south of Vietnam, respectively. The Expressed Population Signal (EPS) for the QNFH record exceeds the generally accepted threshold of 0.85 back to AD 1567, but remains above 0.8 back to 1550. Similar to the MCFH and BDFH records, QNFH expresses statistically significant linkages to regional hydroclimate metrics and the El Niño-Southern Oscillation (ENSO). Here we present a reconstruction of the Standardized Precipitation Evapotranspiration Index (SPEI) for the month of April, averaged over a large region of Southeast Asia. As with prior studies we demonstrate that cool phase (La Niña) and warm phase (El Niño) events are linked to regional wet and dry conditions, respectively, with linkages to modulation of the surface water temperature over the adjacent sea to the east of Vietnam as well as the Indian Ocean. A late 18th century megadrought that is expressed widely across South and Southeast Asia, and notably from the MCFH and BDFH records described above, is not as pronounced in Central Vietnam and we explore the reasons why.

Keywords: Vietnam, dendrochronology, cypress, monsoon, tropical forest, ENSO.

1 Introduction

1.1 Prior dendroclimatic research in Vietnam

Paleo-ecological/climatological studies from the terrestrial tropics are of increasing importance, and are therefore increasingly pursued. In the case of tropical dendrochronology the previously held view that tropical trees cannot be relied upon has been replaced by an understanding that, with effort, some species can be successfully crossdated and used (e.g., Baker et al., 2005; Buckley et al., 1995; 2005; 2007a; 2007b; 2010; 2014; D'Arrigo et al., 1997; 2011; Pumijumnong et al., 1995; 2006; 2011; Sano et al., 2009; 2012; Stahle et al., 2011; 2012; Therrell et al., 2006; Zuidema et al., 2013). The most robust Southeast Asian records have been developed from *Fokienia hodginsii* of the family Cupressaceae. Sano et al. (2009) published the first dendrochronological record of this species from Mu Cang Chai in the north of Vietnam (MCFH), followed by Buckley et al. (2010) from the southern limits of the species range at Bidoup - Nui Ba National Park (BDFH). Here we present the third tree-ring record from this species (QNFH) from Quang Nam Province in central Vietnam (locations shown in **Figure 1**).

The Sano et al. (2009) and Buckley et al. (2010) papers are noteworthy, for they heralded the first successful attempts at passing the rigorous calibration-verification schemes used in dendroclimatology (Cook and Kairiukstis, 1990) for tropical tree growth indices against instrumented climate variables. It should be noted that *Fokienia hodginsii* is the only species from tropical Asia that has been used successfully for climate reconstruction where it has been possible to pass calibration-verification procedures. In both cases noted above, the metric used was the Palmer Drought Severity Index (PDSI, see Palmer et al., 1965), and in both studies it was also shown that sea surface temperature (SST) in the classical "Niño" regions of the central equatorial Pacific were significantly, negatively correlated with the regional hydroclimatology (**Figure 2**) for the beginning or "shoulder" season of the summer monsoon that extends from March to May. In broadly general terms, warm-phase events (El Niño) correspond to regional drought in the early monsoon season as reflected by a reduction in annual radial growth of *Fokienia hodginsii*, while cool-phase events (La Niña) are associated with increased early monsoon moisture and enhanced annual growth. While the Asian Summer Monsoon is the main driver of rainfall for this region, ENSO's influence as described above is clearly felt.

A recent paper by Räsänen et al. (2015) demonstrates that the influence of ENSO events across Southeast Asia exhibits a great deal of spatial variability. This is particularly germane to central Vietnam and the region surrounding the current study site (QNFH), where a large percentage of the annual rainfall comes during the months that transition into the winter dry season (October to December), rather than during the peak of the summer monsoon – a rainfall regime that is unique to this mountainous region (Li et al., 2015; Wang et al., 2015). The pattern of terrestrial rainfall in response to ENSO events for the pre-monsoon season (March – May) is, however, very robust and is evident with the instrumental records as well as with the *Fokienia hodginsii* growth indices as shown in **Figure 2**. Buckley et al. (2010) demonstrated that the two most severe low-growth years in the BDFH record corresponded to the two most notorious El Niño events of the instrumental record – the late 19th century Victorian Holocaust Droughts in 1877-78 and 1888-89, respectively (Davis, 2002). The BDFH record also exhibits a very strong relationship to the Southern Oscillation Index and other measures of ENSO (Buckley et al., 2010). In fact, the ENSO signal in BDFH is robust enough to reconstruct SST over the Niño 3.4 region and pass all calibration-verification statistics, and is similarly responsive to the Interdecadal Pacific

Oscillation (Buckley et al., 2010). Sano et al. (2009) found a similar response to ENSO variability for MCFH, though not as robustly expressed as for BDFH. These correlations with ENSO for the tree ring records are consistent with the same relationships for the instrumental records from both regions (Buckley et al., 2010; Sano et al., 2009).

Another interesting feature noted for the BDFH record was the correspondence of the largest growth index years with years of high rainfall and a linkage to explosive volcanism, as noted by Buckley et al. (2010). Anchukaitis et al. (2010) demonstrated this linkage in greater detail, and they compared these findings with previous model results that did not identify a post-eruption spike in regional rainfall. Xu et al. (2011) have analysed the stable isotopes of Oxygen in the rings of *Fokienia hodginsii* from northern Vietnam and Laos, respectively, and demonstrate further the connection between ENSO events and the hydroclimate over Indochina. Until the current study, however, no crossdated tree growth records have been developed for the central region of Vietnam, a region with a notably different hydroclimate regime that receives a large percentage of its annual rainfall from the months of October to December as demonstrated in **Figure 3**. This peak in rainfall occurs during the transition into the winter monsoon season, which is the dry season across the majority of mainland Southeast Asia including the locations of the MCFH and BDFH sites. The QNFH record that we present here serves to link the northern and southern *Fokienia hodginsii* sites for better regional representation and a first glimpse at the recent paleoclimate history for central Vietnam, a region that has a fundamentally different rainfall regime than regions to the north and south.

1.2 The climate over central Vietnam

The autumnal precipitation regime over central Vietnam is associated with an increase in the occurrence of tropical cyclones (TCs) that pose a significant threat to lives and property, making the region particularly vulnerable to the effects of climate change (McElwee, 2012). Li et al. (2015) identified and analyzed a pronounced decadal oscillation of autumn precipitation in central Vietnam within the 8–11 year frequency band that is modulated by the East Pacific–North Pacific (EP–NP) teleconnection, an ENSO-like variability at lower frequency. The negative phase of the EP–NP pattern is associated with a positive SST anomaly in the semi-closed sea east of Vietnam (commonly referred to as the South China Sea, but in Vietnam it is referred to as the East Sea) that induces low-level convergence, enhances convection, and increases precipitation over Central Vietnam and adjacent Hainan Island (China) and the Philippines. This circulation feature is embedded in the large-scale circulation associated with SST anomalies across the Pacific Ocean, where cooling in the Eastern and Central tropical Pacific is sandwiched between warm anomalies in the North and South Pacific and a warm Western Pacific Ocean. The positive phase of the EP–NP features opposite SST and circulation anomalies and reduced rainfall over central Vietnam (Li et al., 2015). Warming SST and enhanced southerly low-level winds coincide with increased rainfall and TCs, and are part of a hemispheric-scale change in the general circulation in the form of a La Niña-like SST anomaly and a strengthened Walker circulation branch that ascends near Vietnam and the far-western Pacific (Wang et al., 2015).

2 Materials and methods

2.1 The study location

We sampled living *Fokienia hodginsii* trees from Tay Giang Protection Forest in central Vietnam's Quang Nam Province, a location that was until recently only suspected of containing *Fokienia hodginsii*. Our study confirms the existence of old growth *Fokienia hodginsii* on variable terrain between 1,200 and 1,500 meters above mean sea level, amongst what appears as a virtually undisturbed mixed evergreen broadleaved-coniferous forest growing over a humus layer up to 1 m thick. We observed very few signs of human disturbance (e.g., stumps, clearings, etc.), and the fact that such a large and old-aged population of *Fokienia hodginsii* remains in this forest is itself evidence for lack of disturbance, since these trees are highly prized and logged over its entire distribution range. Furthermore, the local Co Tu minority group protects this forest as a local "spirit forest", due to *Fokienia's* history as the wood most sought after for use as coffins by their ancestors. Of the five conifer species found at this site *Fokienia hodginsii*, *Dacrycarpus imbricatus*, *Dacrydium elatum* and *Nageia wallichiana* are canopy emergent, while *Podocarpus neriifolius* comprises a less dominant role in the understory. With the exception of *Fokienia hodginsii*, all of these conifer species are members of the predominantly Southern Hemisphere conifer family Podocarpaceae. We also identified multiple broadleaf species at this site, notably from the canopy dominant families of Magnoliaceae, Fagaceae, Lauraceae and Theaceae (see **Table 1** for a full listing of angiosperms we identified at the study site).

2.2 Vietnamese cypress increment cores

During January 2014 we obtained 112 core samples from 45 mature *Fokienia hodginsii* stems from the Tay Giang Protection Forest (see **Figure 1**). We used Haglof increment borers to extract 5mm diameter dowels of wood that extend from the bark to as near the center of each tree as possible, and from at least two sides of each stem. Every cored tree was georeferenced with

GPS, and all core samples were placed into labeled plastic straw tubes for transport from the forest to the laboratory. Once in the laboratory, all samples were air-dried and then glued into wooden core mounts with their transverse surface exposed. Each core was then surfaced using progressively finer sandpaper and micromesh abrasives in order to reveal the cellular structure of the growth rings, essential for identification of true ring boundaries and occurrences of "false" rings and other anatomical features (Fritts, 1976).

2.3 Crossdating, measuring and quality control

The surfaced cores were analyzed under microscopy at low magnification (7x – 40x) and were crossdated visually with the aid of the skeleton plotting method (Stokes and Smiley, 1968; Fritts, 1976). This proved to be a crucial step for all ensuing analyses due to the complex ring anatomy and growth irregularities (**Figure 4)** that made crossdating difficult in these cores. The absolute dating of growth rings in trees is arguably the most important step in dendrochronology, since without ensuring correct dates for every single ring in sequence, cumulative error is built into the final time series as demonstrated by Fritts and Swetnam (1989) and more recently by Black et al. (2016). In the case of sites where locally absent rings and "false" rings are minimal the error might be marginally consequential to ensuing climate analyses. However, in the case of tropical trees and the *Fokienia hodginsii* from QNFH in particular, a plethora of such problem rings would result in significant error. For example, within our final subset of retained cores 61 of the 22,662 rings analyzed were locally absent (0.27%), and there are numerous examples of false rings that challenged our abilities to accurately identify them (examples shown in **Figure 4)**. Consequently, there were several cores that we were not able to confidently crossdate and these were excluded from further analyses.

Following the rigorous crossdating procedure described above, 71 cores from 37 trees were included in our final ring width index (see **Table 2**). We compared our QNFH master index to the BDFH record (Buckley et al., 2010), which is from a location several hundred kilometers to the south (see **Figure 1**). The two site collections do share some key narrow "marker" growth years (i.e., 2005, 1978, 1889, 1804, 1692, and 1565), as well as many key wide growth years (i.e., 1976, 1875, 1835, 1767, and 1645), and similar comparisons were made with the MCFH site from northern Vietnam. While similarities of key years can be seen between all three sites, several marker years are unique to each site, and significant differences in the low frequency components of these records are clearly expressed. As discussed later in this paper, these expressed differences in tree growth are consistent with the variability of regional climate from the different climate regions of Indochina.

2.4 Indexing radial growth through time

Tree ring standardization aims to remove what is commonly referred to as the "biological growth trend", but is actually the result of stem geometry (i.e., adding the same volume of wood annually to a circumference that increases with each annual increment results in an hypothetical negative exponential decay of the width of rings through time). A second aim is to stabilize the time series variance from juvenile to maturity phases, an issue that is related to the biological growth trend (Fritts, 1976; Cook and Kairiukstis, 1990). For the current study we employed the relatively new method of "signal-free" standardization (SFS), first developed by Melvin and Briffa (2008) and expanded upon by Briffa and Melvin (2011). We utilized program RCSigFree (http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software), a program developed at the Lamont-Doherty Earth Observatory's Tree Ring Lab. The SFS concept is derived from the observation that sequential tree ring measurements are influenced by a wide array of potential time-dependent growth influences that include the temporal variability of climate, internal, biologically-driven processes and stem geometry. SFS attempts to reduce this allocation bias in order to retain the variability of sequential growth that is the sole product of the variability in climate (Briffa et al., 2011). SFS therefore uses division of the common signal into the original measurement data in order to reduce or remove any possible trend distortion in the expressed external forcing signal. This approach requires adjusting the overall trend of the resulting growth indices due to introduction of an arbitrary slope, and as such limits the preservation of variance that exceeds the length of the final timeseries (Melvin and Briffa, 2008). The biweight robust mean was used to calculate the mean-value function for each year's growth index in order to reduce the influence of outliers, and the expressed population signal (EPS) and running RBAR measures of chronology signal strength were calculated using the methods of Wigley et al. (1984). An excellent description of the SFS procedure can be found in Cook et al. (2015) as it was used for the development of the Old World Drought Atlas over Europe. We include the output files and selected graphics of our implementation of this method in the **Supplemental Online Materials**.

2.5 Climate data

We compared the QNFH indices with a variety of climatic data, focusing initially on the same parameters shown by Sano et al. (2009) and Buckley et al. (2010) to be most strongly correlated with the annual growth of *Fokienia hodginsii* (i.e., the Palmer Drought Severity Index or PDSI from Dai et al., 2004; and global SST fields from the Hadley Center in the UK). We also utilized the Standardized Precipitation Evapotranspiration Index (SPEI) obtained from the Global SPEI database (http://sac.csic.es/spei/database.html; Trouet and Van Oldenborgh, 2013). The SPEI data are derived from the Climate Research Unit (University of East Anglia, U.K.) dataset of monthly precipitation and evapotranspiration (CRU TS), which has a spatial resolution of 0.5 degree. Vicente-Serrano et al. (2010) first presented SPEI as an improvement over PDSI as a drought metric in the tropics for studying the effects of global warming on drought severity. As with PDSI, SPEI considers the effect of evapotranspiration on the severity of drought, however SPEI is better suited to a broader set of ecosystems due to its multi-scalar nature, its sensitivity to evapotranspiration demand and its simplicity of calculation (Begueria et al., 2014; Vicente-Serrano et al., 2010; 2013). We therefore elected to pursue SPEI averaged over a 1-month window as our target for reconstruction for this region, rather than PDSI. For analysis, we used the web-based KNMI Climate Explorer (http://climexp.knmi.nl/) for doing basic statistical correlation and regression analyses, as well as statistical packages developed at the Tree Ring Lab of the Lamont-Doherty Earth Observatory such as Principal Components Regression analyses for reconstruction of climate from tree rings.

3 Results and discussion

3.1 Indexed growth at Quang Nam

The stabilized SFS-derived indices of *Fokienia hodginsii* growth at Quang Nam in central Vietnam are presented in **Figure 5.** The fidelity of the common signal at this site is exemplified by an overall series intercorrelation of 0.526, similar to values obtained for MCFH (0.474) and BDFH (0.578), and an EPS value that exceeds the accepted threshold of 0.85 (Wigley et al., 1984) from 1567 out to the present, and exceeds 0.80 from 1550 (see **Figure S4**). QNFH exhibits several periods of above and below average growth over the past five centuries, including a decadal scale low-growth departure at the beginning of the 20th century that is bracketed by two periods of above average growth from about 1860-1890 and from 1920-1950, respectively. Another high growth period is evident during the mid 17th century. The decadal-scale low growth of the latter 18th century that is visible across all of Southeast Asia in prior studies (e.g., Buckley et al., 2007b; 2010; 2014; Cook et al., 2010; D'Arrigo et al., 2011; Sano et al., 2009) appears to be less evident for QNFH, and we contend that this may be the result of the influence of the autumnal rainfall regime that is unique to central Vietnam (see **Figure 3**). We propose that this source of moisture may serve to mitigate the effect of soil moisture deficit that is felt during the subsequent annual dry season, relative to regions to the north and south. In addition, two of the most negative marker years of at BDFH, 1877 and 1889, which reflect the influence of the ENSO-driven late 19th century Victorian Holocaust Droughts (Davis, 2002), are not evident in QNFH. This difference may reflect the modulating effects of local and Indian Ocean SST anomalies as will be discussed in the later part of Section 3.2.

For each of the three *Fokienia hodginsii* records there are periods that are in and out of phase, and it is evident from the 51-year running correlation analyses shown in **Figure 6** that systematic offsets occur between all three regions. Notably, the latter half of the 18th century during the worst of the Strange Parallels Drought (Cook et al., 2010) is a period of strong agreement between the MCFH and BDFH sites, both of which are poorly correlated with QNFH at this time. This suggests that the decadal scale effects of the Strange Parallels Drought were felt more acutely in the northern and southern regions than they were at QNFH, with the central portion of Vietnam showing far less persistent drought for the important "shoulder" monsoon season in

April. Räsänen et al. (2015, Fig. 2) suggests that the boundary of the wet/dry influence of warm phase ENSO events for winter (DJF) as measured from the Multivariate ENSO Index (MEI) falls very near to QNFH, just to the northeast along the Hai Van Pass – a well-known climatic boundary in Central Vietnam at around 16˚ North latitude (e.g., Ho et al., 2011). According to Li et al. (2015) and Wang et al. (2015), local SST in the Sea between Vietnam and the Philippines and farther east over the Philippine Sea also modulate climate over Indochina, adding another source of variability in addition to ENSO. It is plausible that changes in the mean position of this boundary may influence the soil moisture conditions antecedent to the onset of the summer monsoon, a subject worthy of further study.

3.2 Climate-growth relationships

The relationship between QNFH and PDSI, while consistent with prior results from MCFH and BDFH, is more weakly expressed as shown in the left hand panels of **Figure 7**. While Sano et al. (2009) and Buckley et al. (2010) were able to generate robust reconstructions of pre-monsoon PDSI (March-May) from their respective *Fokienia hodginsii* records, the relationship for QNFH is not strong enough to allow for robust statistical reconstruction of this metric. However, as shown in the right hand panels of **Figure 7**, the relationship with the SPEI for the month of April stands out as a month of significant correlation for the QNFH site with a large swath over mainland Southeast Asia. We averaged together the gridded April SPEI measurements from the two regions that are outlined by the black boxes shown in panel (e) **from Figure 7** (data shown in **Figure 8**) and used this as our target metric for reconstruction. The result is a successfully calibrated and verified reconstruction model (**Table 3**) and a reconstruction of April SPEI over mainland Southeast Asia that is plotted in **Figure 9,** and explains 23.3% of the overall variance of the target dataset. While this value may seem somewhat low, the model passes all verification tests when using either half of the record for calibration (**Table 3)**. This is particularly the case with regard to first differenced data, which indicates a high degree of year-to-year variance in common. The coefficient of efficiency statistic (CE) for verification on both halves of the record is consistently positive, and therefore indicates an acceptable amount of model fidelity (Cook and Kairiukstis, 1990).

For comparison purposes a plot of all three Vietnam tree-ring based climate reconstructions, from north to south, is presented in **Figure 10**. The gray shaded boxes within each panel of this plot indicates the period of less confidence based on the EPS, thus limiting our earliest years of comparison to 1650, 1567 and 1250 C.E., respectively. While the response of QNFH to SST over the classic "Niño" regions of the tropical Pacific is similar to that for MCFH and BDFH (**Figure 2)**, the correlation fields are weaker. A look at the relationship between reconstructed April SPEI and temperature at the surface, at the 850mb height and at the 200mb height (**Figure 11**) reveals an apparent inverse relationship between SPEI and temperature over the equatorial zone and the primary areas of ENSO activity in the Pacific, accompanied by an even stronger upper atmospheric La Niña pattern with its accompanying equatorial low-pressure anomalies. An equally strong direct correlation with temperature over the high-elevation of the Tibetan Plateau and most of Eurasia reflects the anomalously strong thermal gradient that develops during the buildup of the annual monsoon that typically forms during La Niña (Shaman and Tziperman, 2005). The 850-hPa height and SLP anomalies depict the broad La Niña features in the Pacific such as the strengthened trade winds, and also highlights a local cyclonic cell over and to the west of Indochina. This local circulation appears to be connected with negative anomalies of

SST in the Indian Ocean, of which the pattern has been identified as the Indian Ocean Basin Mode (IOBM; Yang et al., 2007). It is worth noting that IOBM is not just a passive response to El Niño, and its negative anomaly during April-May can induce a similar atmospheric circulation pattern to the one shown in **Figure 11**.

The out-of-phase relationship and shared decadal spectral coherence between the EP–NP index and autumn precipitation in central Vietnam as presented by Li et al. (2015) may explain an apparent reduction in the severity of the 18^{th} century megadrought at QNFH relative to north and south regions of Vietnam. This inference was derived from the fact that historical severe droughts are mostly multi-year events that are tied to decadal-scale variability. At the interannual scale, Chen et al. (2013) describe another linkage between the winter months climatology on a broader scale with the following year's summer monsoon, and distinguish between years when the East Asian Winter Monsoon (EAWM) is modulated by the effects of ENSO ($EAWM_{EN}$) and those that are not. They demonstrate that a strong (weak) $EAWM_{EN}$ leads to a weak (strong) summer monsoon in the following pre-monsoon months of March-May over a broad swath of Asia that includes our study region. This relationship is also modulated by the strength of the decadal variability that is present in both the Pacific and Indian Oceans (Chen et al., 2013).

Under the inference of the aforementioned large-scale atmospheric anomalies, the regional response in climate can be seen from the strong inverse relationship between April SPEI and maximum temperature over Indochina (**Figure 12**). An increase in early season moisture and cloudiness that would accompany this increased onshore flow ought surely play a role in keeping plants hydrated and cool enough through atmospheric vapor pressure to mitigate the effects of drought. It is clear that the large-scale dynamics of climate play a role in modulating the regional hydroclimate that is reflected in the growth indices of *Fokienia hodginsii* from each of our sites, and further study is warranted. Furthermore, research on the nature of *Fokienia hodginsii's* ecophysiological response to climate (i.e., water, temperature and light) would be an important additional step toward better understanding the results of the current research.

4 Conclusions

This study presents the first tree ring record collected from the mountainous region of central Vietnam and the first climate reconstruction of SPEI for the region – one that passes the rigorous calibration-verification tests commonly used in dendroclimatology. The climate of central Vietnam is distinctly different from the rest of the country in that autumn rainfall is a significant contributor to the annual rainfall totals, more so than the summer monsoon that dominates the rainfall regimes of northern and southern regions, respectively. The mechanism for this is found within the coupled ocean-atmosphere dynamics of the sea to the east of Vietnam and across the global tropics, particularly in the tropospheric circulations. The thermal gradient between the Asian high mountains (the Tibetan Plateau) and the equatorial ocean, notably in the areas closely linked with the ENSO phenomenon, apparently modulates the hydroclimate over Indochina as well. The additional influence of the Northeastern winter monsoon over central Vietnam specifically, and broadly across mainland Southeast Asia during times of strong ENSO and decadal modulation, may provide an important counterbalance to soil moisture deficits generated during particularly severe droughts from the annual dry season. Concurrent SST variations in the Indian Ocean also play a role, and a further connection to increased tropical cyclonic activity during the autumn peak of rainfall may serve to mitigate (or worsen) any spring drought over central Vietnam.

Since the tree ring record and its SPEI reconstruction is the first produced from central Vietnam, more detailed research is needed, particularly with regard to the role of local topography on climate at this site. A deeper, more mechanistic understanding of the physiological controls on the growth of *Fokienia hodginsii* with regard to hydroclimate is needed. In addition, the role of any possible changes in the coupled ocean-atmospheric system over the past millennium needs to be considered in interpreting changes in the regional hydroclimate.

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Table 1. Common angiosperm forest species that coexist with *Fokienia hodginsii* at our study site in Tay Giang Protection Forest, Quang Nam Province, Vietnam.

Factor	Family	Genus	Species
Canopy Dominant	Fagaceae	*Castanopsis*	spp.
		Lithocarpus	spp.
		Quercus	spp.
	Lauraceae	*Cinnamomum*	spp.
		Litsea	spp.
	Magnoliaceae	*Magnolia*	spp.
	Theaceae	*Anneslea*	*fragrans*
		Polyspora	spp.
		Schima	*wallichii*
Below Canopy	Annonaceae	*Polyalthia*	spp.
	Asparagaceae	*Dracaena*	spp.
	Euphorbiaceae	multiple	multiple
	Melastomataceae	*Melastoma*	spp.
		Sonerila	spp.
	Lauraceae	*Cinnamomum*	spp.
		Litsea	spp.
	Moraceae	*Ficus*	spp.
	Primulaceae	*Ardisia*	spp.
	Rubiaceae	*Ixora*	spp.
		Lasianthus	spp.
	Rutaceae	*Clausena*	spp.
		Glycomis	spp.
Herbaceous Layer	Araceae	*Arisaema*	sp.
	Asparagaceae	*Peliosanthes*	cf. *teta*
	Balsaminaceae	*Impatiens*	sp.
	Cyperaceae	*Cyperus*	*leucocephalus*
	Orchidaceae	multiple	multiple
	Piperaceae	*Piper*	spp.
	Poaceae	*Bambusa*	cf. *balcooa*
		Panicum	*notatum*
	Xanthorrhoeaceae	*Dianella*	*ensifolia*
	Zingiberaceae	*Amomum*	spp.
		Globba	spp.
		Zingiber	spp.

Table 2. Details of the QNFH tree ring samples, showing the ID tag for each included tree, the number of cores from each tree that was included in the final indexed record, the first and last years measured (YOM), the number of locally absent rings in each tree (LAB) and the correlation of each tree with the master index (averaged between the total number of cores for each tree).

Tree ID	No. Cores	1st YOM	Last YOM	No. LAB	Corr. Master
TGFH02	1	1628	1740	0	0.434
TGFH03	2	1600	2010	7	0.578
TGFH04	3	1588	2013	2	0.528
TGFH06	2	1570	1800	0	0.431
TGFH07	2	1588	2013	1	0.605
TGFH08	2	1560	2006	0	0.455
TGFH09	2	1550	2013	0	0.482
TGFH10	3	1550	2013	5	0.533
TGFH11	3	1600	2013	3	0.563
TGFH13	3	1347	1970	1	0.521
TGFH15	3	1568	2013	0	0.507
TGFH16	2	1560	1750	1	0.431
TGFH17	2	1550	1808	0	0.462
TGFH19	1	1600	1900	0	0.453
TGFH21	2	1645	2012	3	0.538
TGFH23	1	1575	2011	0	0.458
TGFH25	1	1600	2013	1	0.525
TGFH26	2	1680	2013	4	0.521
TGFH29	3	1573	2013	5	0.495
TGFH30	1	1764	2013	1	0.450
TGFH33	2	1520	1940	2	0.421
TGFH35	3	1582	2013	12	0.521
TGFH37	1	1600	1680	0	0.410
TGFH42	1	1750	2013	0	0.506
TGFH43	3	1680	2013	9	0.582
TGFH44	2	1520	2013	0	0.553
TGFH45	2	1601	2013	0	0.524
TGFH46	1	1567	2013	0	0.537
TGFH47	1	1594	2013	1	0.448
TGFH48	1	1800	2013	0	0.495
TGFH52	1	1870	2013	0	0.486
TGFH54	1	1644	1950	0	0.577
TGFH56	2	1561	1800	0	0.464
TGFH57	3	1600	2013	3	0.562
TGFH58	1	1640	2013	0	0.449
TGFH59	3	1532	2013	0	0.638
TGFH60	2	1700	1959	0	0.584

Table 3. April SPEI reconstruction model results for late calibration (1951-2013 top two tables) and early calibration (1901-1950 bottom two tables) in the left hand columns, and for verification periods as denoted by the (v) in the 3 right hand columns. The * denotes z scores for Sign test and Kendall Tau tests.

Undifferenced Late Calibration (1951-2013) *Verification (1901-1950)*

Test	**Score**	**T stat**	**Prob.**	**Score (v)**	**T-stat (v)**	**Prob. (v)**
Equality of means	0.000	0.000	0.996	-0.094	-0.920	0.639
Cross products mean	0.145	3.041	0.002	0.045	0.953	0.326
Sign test	41+ 22-	*2.268	0.012	34+ 16-	*2.404	0.008
Pearson correlation	r = 0.483	4.311	0.000	r = 0.369	2.753	0.004
Robust correlation	r = 0.447	3.904	0.000	r = 0.419	3.200	0.001
Spearman correlation	r = 0.483	4.304	0.000	r = 0.389	2.927	0.003
Kendall Tau	t = 0.344	*3.982	0.000	t = 0.272	*2.785	0.003
Reduction of error	0.233			0.137		
Coefficient of efficiency	0.233			0.106		

First differenced Late Calibration (1951-2013) *Verification (1901-1950)*

Test	**Score**	**T stat**	**Prob.**	**Score (v)**	**T-stat (v)**	**Prob. (v)**
Equality of means	-0.004	-0.029	0.975	-0.008	-0.060	0.951
Cross products mean	0.506	3.700	0.000	0.215	2.222	0.015
Sign test	41+ 21-	*2.413	0.008	32+ 17-	*2.000	0.023
Pearson correlation	r = 0.659	6.779	0.000	r = 0.493	3.889	0.000
Robust correlation	r = 0.625	6.204	0.000	r = 0.525	4.227	0.000
Spearman correlation	r = 0.658	6.760	0.000	r = 0.481	3.766	0.000
Kendall Tau	t = 0.479	*5.497	0.000	t = 0.344	*3.482	0.000
Reduction of error	0.424			0.241		
Coefficient of efficiency	0.424			0.241		

Undifferenced Early Calibration (1901-1950) *Verification (1951-2013)*

Test	**Score**	**T stat**	**Prob.**	**Score (v)**	**T-stat (v)**	**Prob. (v)**
Equality of means	0.000	0.000	1.000	0.100	1.060	0.289
Cross products mean	0.060	1.588	0.057	0.087	2.344	0.011
Sign test	32+ 18-	*1.838	0.033	45+ 18-	3.276	0.001
Pearson correlation	r = 0.369	2.753	0.004	r = 0.483	4.311	0.000
Robust correlation	r = 0.419	3.200	0.001	r = 0.447	3.904	0.000
Spearman correlation	r = 0.389	2.927	0.003	r = 0.483	4.304	0.000
Kendall Tau	t = 0.272	*2.785	0.003	t = 0.344	3.982	0.000
Reduction of error	0.136			0.227		
Coefficient of efficiency	0.136			0.203		

First differenced Early Calibration (1901-1950) *Verification (1951-2013)*

Test	**Score**	**T stat**	**Prob.**	**Score (v)**	**T-stat (v)**	**Prob. (v)**
Equality of means	-0.008	-0.063	0.948	-0.005	-0.034	0.972
Cross products mean	0.170	2.220	0.015	0.401	3.700	0.000
Sign test	32+ 17-	2.000	0.023	41+ 21-	2.413	0.008
Pearson correlation	r = 0.493	3.889	0.000	r = 0.659	6.779	0.000
Robust correlation	r = 0.525	4.227	0.000	r = 0.625	6.204	0.000
Spearman correlation	r = 0.481	3.766	0.000	r = 0.658	6.760	0.000
Kendall Tau	t = 0.344	3.482	0.000	t = 0.479	5.497	0.000
Reduction of error	0.239			0.387		
Coefficient of efficiency	0.239			0.387		