Chapter 22
Stable Isotopes in Tree Rings of Tropical Forests

Peter van der Sleen, Pieter A. Zuidema, and Thijs L. Pons

22.1 Introduction

The analysis of growth rings in the stems of trees is a relatively new tool in tropical forests, as the existence of annual rings in tropical trees was not commonly recognized until recently. For a long time, the tropical environment was associated with year-round favorable growth conditions that were thought to prevent the formation of distinct annual growth rings. However, most tropical environments are seasonal to a various extent (Fig. 22.1), and the formation of annual tree rings in deciduous species growing in tropical climates with a pronounced dry season has been known for a long time (Coster 1927). Although ring boundaries of trees in the humid tropics are generally less clear than those in temperate trees, the formation of distinct annual growth rings has been shown for a large number of tropical tree species (Worbes 2002; Rozendaal and Zuidema 2011; Zuidema et al. 2012; Brienen et al. 2016; Schöngart et al. 2017). In addition to drought, other seasonally changing environmental factors, such as flooding and soil salinity, are known to induce the formation of annual ring boundaries (Schöngart et al. 2002; Chowdhury et al. 2008).

Supplementary Information The online version contains supplementary material available at (https://doi.org/10.1007/978-3-030-92698-4_22).

P. van der Sleen (✉) · P. A. Zuidema
Forest Ecology and Forest Management Group, Wageningen University and Research,
Droevendaalsesteeg 3, 6708 PB Wageningen, The Netherlands
e-mail: peter.vandersleen@wur.nl

P. van der Sleen
Wildlife Ecology and Conservation Group, Wageningen University and Research,
Droevendaalsesteeg 3, 6708 PB Wageningen, The Netherlands

T. L. Pons
Plant Ecophysiology, Institute of Environmental Biology, Utrecht University, Padualaan 8, 3584
CH Utrecht, The Netherlands

R. T. W. Siegwolf et al. (eds.), *Stable Isotopes in Tree Rings*, Tree Physiology 8,
https://doi.org/10.1007/978-3-030-92698-4_22

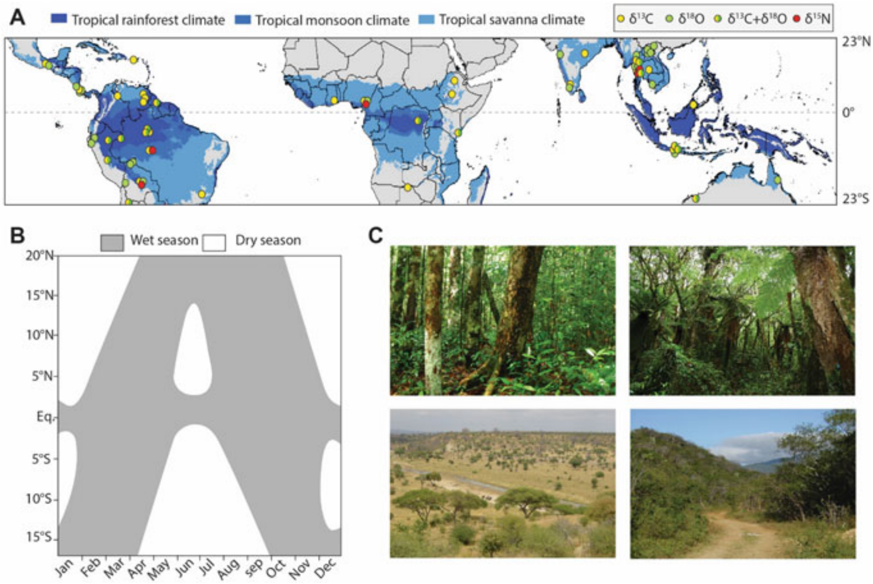

Fig. 22.1 **a** Map of the tropics showing locations of studies on stable isotopes in tropical tree-rings. Main findings of these studies summarized in Table 22.1. Background map showing tropical climates according to Köppen classification (map from Beck et al. 2018), with grey continental areas belonging to arid (mostly treeless) climate types. **b** Diagram showing general rainfall seasonality in the tropics, with a dry month defined as a month with <100 mm average precipitation. Figure adapted from Kricher (2011). **c** A few examples of tropical (woody) ecosystems. Clockwise from top left: evergreen rainforest close to the equator (no dry season) in Brazil, mountain cloud forest in Bolivia (moderate dry season; but moist year round), deciduous dry forest in Mexico (long dry season), and savanna vegetation in Tanzania (long dry season)

The "re-discovery" of annual growth-ring formation in tropical trees, and developments in stable isotope analyses has triggered studies on the variation of the natural abundance of isotopes in tropical trees, with the number of publications on stable isotopes in tropical tree rings increasing rapidly in recent years (Fig. 22.1). In this chapter, we provide an overview of research on stable isotopes in tropical tree rings, and the insights gained on the functioning of tropical forests and the impacts of global change. This chapter is a condensed and updated version of our earlier review (van der Sleen et al. 2017), with a main focus on lowland forests in the wet tropics between 23.5°N/S (Fig. 22.1).

22.2 Tropical climate

The tropics are generally warm (mean annual temperature of >24 °C) and wet (except for dry grasslands and deserts). Most tropical ecosystems are seasonal to some extent, but in contrast to temperate regions, seasonal weather patterns are primarily driven by variation in precipitation amount and not temperature fluctuations. Across the tropics, rainfall seasonality is a result of large-scale atmospheric circulation patterns. At the equator, heat builds up, causing warm and moisture-laden air to rise. The ascending air diverges at the top of the troposphere and flows to more northern and southern latitudes. As the air cools, it loses its moisture as precipitation, becomes more dense, and ultimately descends as dry air in the subtropics, from where it returns equatorward near the surface, giving rise to the trade winds. These circulation patterns, on both the northern and southern hemisphere, are called the Hadley cells. The great equatorial convection zone, where the trade wind meet is known as the Intertropical Convergence Zone (ITCZ), and characterized by violent thunderstorms and high quantities of precipitation. The ITCZ moves north during the Northern hemisphere summer, and south during the austral summer, as a consequence of the Earth´s tilt. This seasonal movement induces wet and dry seasons in most tropical regions (Fig. 22.1). At locations lacking a true dry season, forests will remain evergreen throughout the year. At locations with a longer or drier dry season, the number of deciduous species increases. Further away from the Equator, forests give way to savanna, shrubland or grassland (Fig. 22.1). Although climate is an important factor determining forest type, it is also affected by other factors, such as soil characteristics and fire regime.

Another important climatic feature in tropical regions is the El Niño–Southern Oscillation (ENSO), which are irregular periodic variations in winds and sea surface temperatures over the tropical eastern Pacific Ocean. Although the factors responsible for the occurrence of ENSO events remain incompletely understood, the phenomenon occurs when the ITCZ migrates more southwards than normal. This raises sea surface temperature and disrupts the normal upwelling pattern along the west coast of South America. Eventually, this reduces the transport of warm surface water across the Pacific Ocean toward Asia, and as a result affects weather systems throughout the tropics and subtropics, causing heavy downpours and flooding in some regions and severe droughts in others. El Niño occurs every two to seven years and tends to alternate with another climatic phenomenon with opposite effects. This is called La Niña, and happens when trade winds gain abnormal strengths, increasing upwelling along the west Coast of South America and strengthening the flow of warm surface water westwards across the Pacific.

Local climate conditions, and its variability (including ENSO-driven anomalies), affect tree physiology and thus tree-ring isotope values. In addition, large-scale circulation patterns affect the $\delta^{18}O$ signature of precipitation, which can be recorded in tree rings (Table 22.1).

Table 22.1 Summary of the main usage and outcomes of studies measuring stable isotopes in tropical tree rings. References given in chronological order (detailed version of the table is available, see Supplementary Table S1)

Stable isotope	Main usage	Main outcome	Number of species*	References
^{13}C	Proxy for iWUE	iWUE generally increased over time	21(3)	Hietz et al. (2005), Brienen et al. (2011), Loader et al. (2011), Locosselli et al. (2013), van der Sleen et al. (2015a), Rahman et al. (2020)
	Identification of annual rings in ring-less wood	Moderate potential to identify annual rings through intra-annual sampling	12(8)	Leavitt and Long (1991), Ohashi et al. (2009), Krepkowski et al. (2013), Schubert and Timmermann (2015)
	Unravelling isotope-climate relationships	Negative correlation with rainfall	16(0)	Gebrekirstos et al. (2009), Fichtler et al. (2010), Brienen et al. (2011), Gebrekirstos et al. (2011), van der Sleen et al. (2014), Schubert and Timmermann (2015), Boakye et al. (2019)
	Reconstruction of past climate	Some prospect for rainfall reconstruction	1(0)	Wils et al. (2010), Mokria et al. (2018)
^{18}O	Unravelling isotope-climate relationships	Correlations with rainfall, humidity and ENSO in shallow rooting trees	11(0)	Anchukaitis et al. (2008), Anchukaitis and Evans (2010), Managave et al. (2011b), Managave et al. (2011a), Xu et al. (2011), Brienen et al. (2012), Zhu et al. (2012a), Zhu et al. (2012b), Sano et al. (2012), Brienen et al. (2013), Xu et al. (2013), Boysen et al. (2014), van der Sleen et al. (2015b), Schollaen et al. (2015), Xu et al. (2015), Volland et al. (2016), Cintra et al. (2019)

(continued)

Table 22.1 (continued)

Stable isotope	Main usage	Main outcome	Number of species*	References
	Reconstruction of past climate	Good prospect for rainfall reconstruction	14(0)	Managave et al. (2011b), Managave et al. (2011a), Brienen et al. (2012), Zhu et al. (2012a), Zhu et al. (2012b), Sano et al. (2012), Xu et al. (2013), van der Sleen et al. (2015b), Baker et al. (2015), Xu et al. (2015), Pumijumnong et al. (2020)
	Identification of annual rings in ring-less wood	Good potential to identify annual rings through intra-annual sampling	6(6)	Evans and Schrag (2004), Evans (2007), Anchukaitis et al. (2008), Managave et al. (2010), Xu et al. (2014)
^{13}C and ^{18}O	Identification of annual rings in ring-less wood	Good potential to identify annual rings through intra-annual sampling	20(17)	Verheyden et al. (2004), Poussart et al. (2004), Poussart and Schrag (2005), Pons and Helle (2011), Ohashi et al. (2016), Managave et al. (2017), Cintra et al. (2019)
	Unravelling isotope-climate relationships	Correlations with rainfall and ENSO	6(0)	Cullen and Grierson (2007), Ballantyne et al. (2011), Schollaen et al. (2013), Colombaroli et al. (2016), Managave et al. (2017)
	Identification of drivers of changes in iWUE (stomatal conductance vs. photosynthesis)	Some evidence that iWUE increased through decreased g_s	4(0)	Cullen et al. (2008), Nock et al. (2011)
^{15}N	Effects of increased N deposition on N cycling	Potential to record aspects of nitrogen cycle	9(0)	Hietz et al. (2010), Hietz et al. (2011), van der Sleen et al. (2015c)

ENSO, el Niño Southern Oscillation; iWUE, intrinsic water-use efficiency; g_s stomatal conductance

[*] Total number of species and those with non-distinct growth rings between brackets. Some species were involved in multiple studies, notable *Tectona grandis*, *Cedrela odorata*, and *Fokienia hodginsii*

22.3 Carbon Stable Isotopes

22.3.1 Carbon Isotope Ecophysiology in the Tropics

The stable carbon isotopic signature in the wood of tropical trees is influenced by a variety of factors related to rainfall, temperature, light conditions and species' responses to drought (for the basics of the $^{13}C/^{12}C$ isotope fractionation in plants see Chap. 9). The combined effects of these factors determine $\delta^{13}C$ values measured in tropical tree rings. In some cases, contributions of individual environmental factors are hard to disentangle, as they can covary and exert similar effects on tree-ring $\delta^{13}C$.

Ontogenetic trends in tree-ring $\delta^{13}C$ series can be substantial for tropical trees, as was illustrated for *Cedrela odorata* from Bolivia (Brienen et al. 2017). Juvenile trees growing under a forest canopy are exposed to reduced irradiance that is associated with a high ratio of intercellular over atmospheric CO_2 concentration (c_i/c_a), and young trees possibly also absorb ^{13}C-depleted CO_2 near the forest floor (Medina and Minchin 1980; Medina et al. 1991; Buchmann et al. 1997). Both factors contribute to low $\delta^{13}C$ values in the stem wood of small trees. Sub-canopy trees are exposed to higher light levels and slightly ^{13}C-enriched CO_2 due to high photosynthetic activity in the canopy, leading to higher $\delta^{13}C$ values in their wood. Canopy and emergent trees are exposed to high light levels and CO_2 with an atmospheric $\delta^{13}C$ signature (Buchmann et al. 1997). In addition, ontogenetic trends in tree-ring $\delta^{13}C$ may be driven by increased vapor pressure deficit (VPD) from understory to canopy and increases in hydraulic resistance with tree height. Therefore, changes in $\delta^{13}C$ with tree size can provide valuable information in an ecological context (e.g. on light conditions; van der Sleen et al. 2014), but are an important confounding factor in a dendroclimatological context.

Decreasing water availability, or increasing VPD, results in stomatal closure, and therefore lowers the C_i/C_a ratio (e.g. Gebrekirstos et al. 2011). As a result, drought increases tree-ring $\delta^{13}C$ values and intrinsic water-use efficiency (iWUE; the ratio of photosynthetic rate over stomatal conductance; A/g_s) (e.g. Lambers et al. 2008; Cernusak et al. 2009; Craven et al. 2013). The available evidence suggests that the relationship between water availability and tree-ring $\delta^{13}C$ also holds in regions with humid climatic conditions: $\delta^{13}C$ of leaves collected in the rainy season was lower than in leaves collected in the dry season (French Guyana, Buchmann et al. 1997), and wood $\delta^{13}C$ of trees growing near a creek was lower than that of trees growing on a comparatively drier ridge (Guyana, Pons et al. 2005).

Changes in light and nutrient conditions can also affect tree-ring $\delta^{13}C$ values when photosynthetic activity increases (A) more that stomatal opening (g_s) (e.g. Cernusak et al. 2009; van der Sleen et al. 2014). Interestingly, average tree-ring $\delta^{13}C$ values and the impact of environmental conditions on $\delta^{13}C$ ratios is species specific. Co-occurring tree species of similar DBH can exhibit large variations in $\delta^{13}C$ values, which has been related to differences in successional status (Bonal et al. 2007), shade tolerance (Guehl et al. 1998; Bonal et al. 2000), leaf phenology patterns (Bonal et al. 2000), and drought tolerance (Craven et al. 2013).

22.3.2 Seasonal Variation in Tree-Ring $\delta^{13}C$

Early studies on δ^{13}C in tropical wood showed the presence of intra-annual variation, similar to what was found for other climatic regions (Leavitt and Long 1991). Subsequent studies confirmed this seasonality (e.g. Poussart et al. 2004; Verheyden et al. 2004; Ohashi et al. 2009), suggesting seasonal variation in water availability as underlying cause. Variation in δ^{13}C within a single growth ring can however, not be unequivocally understood from current photosynthesis on the basis of the Farquhar et al. (1989) model. Other processes may interfere with patterns driven by climate seasonality, such as utilization of stored reserves early in the growing season, potential fractionation downstream from the carbon fixation in the leaves, and a varying fraction of C allocated to other processes than diameter increment in the growing season (Helle and Schleser 2004; Kagawa et al. 2006; Krepkowski et al. 2013; Fu et al. 2017). Although attempts have been made to identify annual rings in tropical trees that lack visible increment ring boundaries based on intra-annual δ^{13}C patterns, δ^{18}O proved to be more useful for that purpose.

22.3.3 Annual and Decadal Variation in Tree-Ring $\delta^{13}C$

Several studies have investigated the inter-annual variation of δ^{13}C and its correlation with precipitation amount (Table C). Strong negative correlations between tree-ring δ^{13}C and annual precipitation were found for species from various sites in tropical America, Asia and Africa, whose growing conditions differed widely in annual precipitation (e.g. Fichtler et al. 2010; Rahman et al. 2020). Such climate sensitivity was further linked to ENSO variability in some studies (e.g. Brienen et al. 2011). In semi-arid Ethiopia, Gebrekirstos et al. (2009) also found a strong correlation of δ^{13}C with precipitation for three *Acacia* species, but less so in *Balanites aegyptiaca*. Such differences may relate to water-use strategies, with drought-tolerant species showing a lower sensitivity to inter-annual variability in precipitation amount (Gebrekirstos et al. 2011; Craven et al. 2013).

Other studies combined δ^{13}C sequences with measurements of δ^{18}O. In some of these, δ^{13}C showed correlation with other precipitation variables than those found for δ^{18}O (Cullen and Grierson 2007; Schollaen et al. 2013). Nevertheless, δ^{18}O series generally yielded stronger correlations with precipitation variables than δ^{13}C series (Poussart and Schrag 2005; Ballantyne et al. 2011: and see discussion in the next section).

Studies using longer tree-ring sequences have consistently shown a declining δ^{13}C trend over the last century in tropical trees (Hietz et al. 2005; Brienen et al. 2011; Loader et al. 2011), also when explicitly correcting for potential ontogenetic effects (Nock et al. 2011; van der Sleen et al. 2015a). After correcting for decreasing atmospheric δ^{13}C over that period (the Suess effect), a rather constant ^{13}C discrimination (Δ^{13}C) generally remains. This leads to the conclusion that C_i/C_a remained constant over time and that, as a result of the increasing atmospheric CO_2 concentration, iWUE has increased consistently over time (Silva and Anand 2013, see Chap. 17). A sustained increase of photosynthesis and/or a higher water-use efficiency under elevated CO_2 are expected to stimulate tree growth if carbon and/or water are limiting factors (Körner 2009). A few studies also quantified temporal trends in tree growth using the same tree-ring sequences as used to determine $\delta^{13}C$ trends (Nock et al. 2011; van der Sleen et al. 2015a). Interestingly, these studies found no indications for a growth stimulation over the past century. Stem diameter growth is not necessarily linearly linked to photosynthetic activity, because other aspects of the carbon balance of trees may have changed as well, such as phenology, leaf turnover, respiration and biomass allocation. However, if it is reasonable to assume that diameter growth can reflect changes in the total carbon balance of a tree, in particular on longer time scales, than the available tree-ring studies suggest that photosynthesis did not increase as a result of rising atmospheric CO_2 concentration. This scenario could arise if tree growth is ultimately limited by nutrient availability in most tropical regions, or if a CO_2-induced stimulation of photosynthesis has been compensated by an external climate-related stressor, such as increased temperature or decreased precipitation.

22.4 Oxygen Stable Isotopes

22.4.1 Oxygen Stable Isotope Ecophysiology in the Tropics

Water taken up by trees becomes enriched in ^{18}O in leaves as a result of transpiration. The strength of this enrichment is mediated by environmental conditions (Barbour 2007; Chap. 10). CO_2 taken up by the leaves exchanges its oxygen atoms with that of leaf water, causing a transfer of the isotopic signature of leaf water to sucrose. In addition, when cellulose is synthesized from sucrose in the stem, about 42% of the oxygen atoms are again exchanged with xylem water. This exchange causes the effect of enriched leaf water to be partly reverted, and results in a strong imprinting of the isotope signature of source water in the wood of trees. Unfortunately, the $\delta^{18}O$ signature of absorbed source water is commonly unknown, especially over longer time scales. In addition, it is often unknown from what depth the root systems of tropical trees take up water, which further complicates the determination of the $\delta^{18}O$ of source water, and thus the interpretation of intra- and inter-annual variation in $\delta^{18}O$ in wood. Shallow-rooting trees, growing in dense canopies where isotopic enrichment at the soil surface is minimal, likely absorb water that consists mainly of recent precipitation, and hence tree-rings are imprinted with an ^{18}O signal that is rather similar to that of rainwater. As rainwater resides only shortly at the soil surface before percolating down to the groundwater, the $\delta^{18}O$ signature of groundwater likely integrates variation in $\delta^{18}O$ in precipitation over several years (Chap. 18). The depth of water uptake has been estimated by measuring natural abundance of ^{18}O in the soil profile and in xylem water (Jackson et al. 1995; Hasselquist et al. 2010; Ellsworth and Sternberg 2015) or by labelling soil water (Stahl et al. 2013). These studies show that deciduous trees tend to take up water from shallower depths than evergreen trees and that the depth of water uptake generally increases with tree age and size.

22.4.2 Seasonal Variation in Tree-Ring $\delta^{18}O$

The first $\delta^{18}O$ studies on tropical trees quantified radial variation of $\delta^{18}O$ in tree stems to reconstruct annual ring boundaries of tree species without anatomically distinct rings or to confirm the annual nature of ring formation (Evans and Schrag 2004; Poussart et al. 2004; Verheyden et al. 2004; Poussart and Schrag 2005; Evans 2007). In some of these studies, $\delta^{13}C$ was also measured, but $\delta^{18}O$ was found to be generally superior for this purpose. The suitability of $\delta^{18}O$ for the identification of annual rings is based on its seasonal change in precipitation: rainwater $\delta^{18}O$ is low during the rainy season and with heavy precipitation events (Dansgaard 1964; Villacıs et al. 2008; Kurita et al. 2009). High $\delta^{18}O$ values of precipitation during the dry season can be further amplified in both soil and leaves due to higher evaporation at low humidity (Jackson et al. 1995; Cintra et al. 2019). This seasonality in $\delta^{18}O$ was confirmed in tropical trees with distinct annual rings (Poussart et al. 2004; Managave et al. 2010; Ballantyne et al. 2011; Managave et al. 2011a; Schollaen et al. 2013). The identification of annual rings in homogeneous (ring-less) wood is most successfully done when intra-annual variation in source $\delta^{18}O$ is large. This is the case in the western parts of the Amazon basin, where $\delta^{18}O$ in precipitation is low in the rainy season due to rain-out of the heavy isotopes as water vapor travels from the Atlantic ocean across the basin (Sturm et al. 2007). Evidence for this effect is provided by the lower intra-annual variation in $\delta^{18}O$ in evergreen trees from Guyana (1–4‰; Pons and Helle 2011) compared to trees sampled near Manaus, Brazil (3–6‰; Ohashi et al. 2016). A special case are trees in montane forests where the uptake of water during the rainy season is from precipitation, whereas moisture can also be directly absorbed from clouds in the dry season. These two water sources differ in $\delta^{18}O$ values, which can result in large seasonal variation of tree-ring $\delta^{18}O$ (Anchukaitis et al. 2008; Anchukaitis and Evans 2010). As the strength of intra-annual variation in $\delta^{18}O$ varies across species (Poussart and Schrag 2005; Anchukaitis et al. 2008) and climatic conditions, selection of species and sites will determine the ability to identify annual rings in homogeneous wood.

22.4.3 Annual and Decadal Variation in Tree-Ring $\delta^{18}O$

Because some trees incorporate the $\delta^{18}O$ signature of rainwater in stem wood, time series of tree-ring $\delta^{18}O$ can be used to quantify past variability in precipitation. Tree-ring $\delta^{18}O$ has been correlated with basin-wide precipitation in the Amazon

(Ballantyne et al. 2011; Brienen et al. 2012; Baker et al. 2015, 2016), and regional precipitation in Thailand (Poussart and Schrag 2005; Pumijumnong et al. 2020), Costa Rica (Anchukaitis and Evans 2010), India (Managave et al. 2011b), Indonesia (Schollaen et al. 2013, 2015), Laos and Vietnam (Xu et al. 2011), West Africa (van der Sleen et al. 2015b), and central Africa (Colombaroli et al. 2016). Particularly El Niño Southern Oscillation (ENSO) variability is often evident in δ^{18}O sequences either from positive anomalies (Verheyden et al. 2004; Anchukaitis and Evans 2010; Zhu et al. 2012a) or negative ones (Evans and Schrag 2004; Brienen et al. 2012). The analysis of tropical tree-ring δ^{18}O is developing into a powerful tool for reconstructing the variability of precipitation on regional scales.

Good synchronization of δ^{18}O patterns among individual trees was found for several species (e.g. Poussart and Schrag 2005; Managave et al. 2011b; Brienen et al. 2012; van der Sleen et al. 2015b), sometimes over large spatial distances (Baker et al. 2015; Schwendenmann et al. 2015; Volland et al. 2016). Synchronous variability in δ^{18}O can be higher than for ring-width, thus providing an alternative tool for cross dating (Baker et al. 2015; van der Sleen et al. 2015b; Volland et al. 2016) and identification of false and missing rings (Boysen et al. 2014). However, δ^{18}O synchronization between individuals may be low for certain species or sites (e.g. Poussart and Schrag 2005; Baker et al. 2015). For δ^{18}O in *Toona ciliata* from Thailand, low δ^{18}O synchronization occurred (van der Sleen 2014), in spite of the ring-width series showing strong synchronization (Vlam et al. 2014). It is likely that trees that lack a common signal in tree-ring δ^{18}O values exploit other water sources than recent precipitation (e.g. ground water). These results suggest that shallow rooting tree species on well-drained soils have the highest probability to record the δ^{18}O variability of precipitation and thus have the highest potential as tools for climate reconstructions.

In several studies the two stable isotopes ^{18}O and ^{13}C were combined using a mechanistic interpretation, the so-called dual isotope approach (see Chap. 16), where A/g_s obtained from Δ^{13}C and g_s derived from Δ^{18}O could potentially provide an estimate of A (Scheidegger et al. 2000). This approach was used by Nock et al. (2011), who interpreted an increase of Δ^{18}O over time as an indication of a decreasing g_s in trees from Thailand. The observed decrease of Δ^{13}C, and thus increasing A/g_s, would then be the result of this decreasing g_s and not an increasing A. However, the underlying assumptions in this approach are that the δ^{18}O signature of source water is known and that the leaf to air vapor pressure difference (LAVPD) has remained constant over the period studied. In many tropical regions, this LAVPD may have increased as a result of global warming and/or decreased precipitation, leading to increased transpiration and δ^{18}O over time. Even though g_s is also partly controlled by LAVPD, this makes it nonetheless difficult to separate the g_s effect from the LAVPD effect on transpiration.

A long-term increase of δ^{18}O values has been encountered in several studies conducted on tropical tree species (Poussart and Schrag 2005; Xu et al. 2011; Brienen et al. 2012; van der Sleen 2014; van der Sleen et al. 2015b; Volland et al. 2016). Some of these trends could be caused by ontogenetic changes, but a consistent small trend over the past century was also found in studies that did correct for ontogenetic trends (van der Sleen 2014; van der Sleen et al. 2015b; Volland et al. 2016). For the Amazon region, these results are consistent with similar increases of $\delta^{18}O$ in Andean ice cores (Thompson et al. 2006) and Andean lake sediments (Bird et al. 2011). Thus, the increasing trend in $\delta^{18}O$ in tree rings likely reflects a pan-tropical phenomenon. The cause of this increase is yet unknown, and it is unclear whether it relates to climate change.

22.5 Nitrogen Stable Isotopes

22.5.1 Nitrogen Stable Isotope Ecophysiology

The value of plant $\delta^{15}N$ depends on the $\delta^{15}N$ of the N taken up and N losses in leaves, fruits, etc. Uptake can be in the form of nitrate, ammonium, organic N compounds or N_2 in the case of nitrogen fixation. The $\delta^{15}N$ of these sources varies in a complex manner (except for N_2, which is used as standard and is thus 0‰ by definition; Chap. 12).

Higher soil and foliage $\delta^{15}N$ are generally reported for tropical lowland forests, compared to temperate and boreal forests (Martinelli et al. 1999; Amundson et al. 2003), and tropical montane forest (Brearley 2013). This pattern is considered as evidence of more N losses and thus a more open N cycle in tropical lowland forests, because nitrate lost through leaching and/or denitrification is ^{15}N-depleted. Temperate forests are generally more N-limited, whereas tropical forests tend to be more P-limited (Vitousek and Howarth 1991), which is consistent with their higher $\delta^{15}N$. Leguminous trees are abundant in tropical forests, although not all can form an effective symbiosis with Rhizobia. Yet, facultative leguminous N_2-fixers can still be abundant (Menge and Chazdon 2016) and contribute to N-accumulation also in late successional stages of tropical forests (Roggy et al. 1999; Pons et al. 2007). This could be the reason for an alleviation of N-limitation, whereas N_2-fixing trees are virtually lacking in temperate forest (except for early successional stages; Menge et al. 2009).

22.5.2 Annual and Decadal Variability in Tree-Ring $\delta^{15}N$

So far, only three studies on temporal variation or trends $\delta^{15}N$ in tree rings have been carried out in tropical forests (Hietz et al. 2010, 2011; van der Sleen et al. 2015c). Hietz et al. (2010) using two species in a Brazilian forest, found a gradual increase of tree-ring $\delta^{15}N$ over time after statistical correction for tree age. The authors suggested that this result could be caused by an increase in tree turnover and thus gap formation that generates NO_3^- losses and thereby increasing $\delta^{15}N$ of the remaining soil N pool. In a subsequent study, Hietz et al. (2011) reported also an increase in $\delta^{15}N$ in three species from a monsoon forest in Thailand. They also found a similar increase when comparing 40-year-old herbarium leaves with recent leaves from the same species and sample location in a Panamanian forest (BCI). The two forests are intensively monitored and there are no indications that the level of disturbance has increased over the past century. Such a consistent trend in $\delta^{15}N$ in three widely separated tropical forests may therefore indicate an effect of increased anthropogenic N-deposition, which causes higher NO_3^- losses (and thus $\delta^{15}N$ enrichment of remaining soil nitrogen). However, in the most recent study, van der Sleen et al. (2015c) sampled annual rings in six species from three sites at different continents. They corrected for possible tree size effects by comparing wood sampled at a fixed diameter (20 cm) from different sized trees. Ten-year pooled samples were also collected between 1955 and 2005 from single trees, which showed increasing trends of $\delta^{15}N$ in Bolivia and Cameroon. Surprisingly, the trends were absent in the fixed diameter sampling, showing evidence of potential ontogenetic effects. The discrepancy between the results of Hietz et al. (2011) and van der Sleen et al. (2015c) may also have been caused by a lower statistical power in the latter. Unfortunately, the interpretation of temporal changes in $\delta^{15}N$ in the few available tropical tree-ring studies remain strongly hampered by a limited understanding of the factors that influence soil- and tree $\delta^{15}N$ values.

22.6 Conclusion and Perspective

Tropical forests harbor an incredible biodiversity and provide ecosystem services on which millions of people depend. They are a major component of the global carbon cycle, storing some 25% of the total terrestrial carbon and accounting for a third of net primary production (Bonan 2008). Understanding the functioning of these forests and their responses to global change is therefore an urgent need for ecology, climate science and conservation. The study of stable isotopes in tropical tree rings offers unique opportunities to quantify how these trees respond to their environment, and can fill an important void in many tropical areas where the availability of climate data is limited or of short duration. In fact, stable isotopes in tree rings are essentially the only tools available to obtain cost-effective, high-resolution, long-term retrospective data on tree physiology and the environmental conditions affecting it.

Currently, stable isotopes research in the tropics has mainly focused on (i) quantifying the effects of rising atmospheric CO_2 and climate change on tree physiology, (ii) identifying the drivers of growth variability and reconstruction of past climate, and (iii) the identification of annual rings in wood lacking anatomically distinct growth boundaries. The main findings of the available studies are shortly summarized for each isotope in Table 22.1. The application of stable isotopes continues to expand. New applications are numerous, and include the potential use of stable isotopes for timber tracing and to identify illegally logged wood (e.g. Vlam et al. 2018), to benchmark the predictions of dynamic global vegetation models (e.g. Zuidema et al. 2018), and for reconstructions of atmospheric CO_2 and $\delta^{13}C$ values (using trees with a C4 photosynthetic pathway; Ben et al. 2017).

Although tropical isotope research has centered on three stable isotopes (C, O, and to a lesser degree N), advances in analytical techniques and reductions in associated costs continue to broaden these analyses. This not only includes the analyses of other stable isotopes, but also the analyses of the intramolecular distribution of isotopes. For example, the position of ^{18}O in the glucose moiety in cellulose can be used to separate source water from leaf water enrichment effects (Sternberg 2009; Waterhouse et al. 2013), and the position of ^{2}H was related to the oxygenation/carboxylation ratio that depends on C_{i} (Ehlers et al. 2015). These techniques can be used to infer more details about environmental effects on tropical trees than is possible with bulk isotopic ratios as done so far. Even though stable isotope research in the tropics still faces methodological and interpretation issues, we anticipate that it will continue to play a crucial role for our understanding of the functioning of tropical forests and their resilience to global change.

References

Amundson R, Austin AT, Schuur EAG, Yoo K, Matzek V, Kendall C, Uebersax A, Brenner D, Baisden WT (2003) Global patterns of the isotopic composition of soil and plant nitrogen. Glob Biogeochem Cycles 17:31–31

Anchukaitis KJ, Evans MN, Wheelwright NT, Schrag DP (2008) Stable isotope chronology and climate signal calibration in neotropical montane cloud forest trees. J Geophys Res G Biogeosciences 113

Anchukaitis KJ, Evans MN (2010) Tropical cloud forest climate variability and the demise of the Monteverde golden toad. Proc Natl Acad Sci USA 107:5036–5040

Baker JC, Hunt SF, Clerici SJ, Newton RJ, Bottrell SH, Leng MJ, Heaton TH, Helle G, Argollo J, Gloor M, Brienen RJ (2015) Oxygen isotopes in tree rings show good coherence between species and sites in Bolivia. Glob Planet Chang 133:298–308

Baker JCA, Gloor M, Spracklen DV, Arnold SR, Tindall JC, Clerici SJ, Leng MJ, Brienen RJW (2016) What drives interannual variation in tree ring oxygen isotopes in the Amazon? Geophys Res Lett 43:11831–11840

Ballantyne AP, Baker PA, Chambers JQ, Villalba R, Argollo J (2011) Regional differences in South American monsoon precipitation inferred from the growth and isotopic composition of tropical trees. Earth Interact 15:1–35

Barbour MM (2007) Stable oxygen isotope composition of plant tissue: a review. Funct Plant Biol 34:83–94

Beck HE, Zimmermann NE, McVicar TR, Vergopolan N, Berg A, Wood EF (2018) Present and future Koppen-Geiger climate classification maps at 1-km resolution. Sci Data 5

Ben T, Hart PJ, Helle G (2017) Towards establishing a new environmental archive—annual growth periodicity, stable carbon isotope variability and reconstruction potential of ’akoko (*Euphorbia olowaluana*), a native Hawaiian tree with C-4 photosynthetic pathway. Erdkunde 71:77–92

Bird BW, Abbott MB, Vuille M, Rodbell DT, Stansell ND, Rosenmeier MF (2011) A 2,300-year-long annually resolved record of the South American summer monsoon from the Peruvian Andes. Proc Natl Acad Sci USA 108:8583–8588

Boakye EA, Gebrekirstos A, Hyppolite DN, Barnes VR, Porembski S, Brauning A (2019) Carbon isotopes of riparian forests trees in the savannas of the Volta sub-basin of Ghana reveal contrasting responses to climatic and environmental variations. Forests 10:251

Bonal D, Atger C, Barigah TS, Ferhi A, Guehl JM, Ferry B (2000) Water acquisition patterns of two wet tropical canopy tree species of French Guiana as inferred from (H_2O)-O-18 extraction profiles. Ann For Sci 57:717–724

Bonal D, Born C, Brechet C, Coste S, Marcon E, Roggy JC, Guehl JM (2007) The successional status of tropical rainforest tree species is associated with differences in leaf carbon isotope discrimination and functional traits. Ann For Sci 64:169–176

Bonan GB (2008) Forests and climate change: forcings, feedbacks, and the climate benefits of forests. Science 320:1444–1449

Boysen, BMM, Evans MN, Baker PJ (2014) $\delta^{18}O$ in the tropical conifer *Agathis robusta* records ENSO-related precipitation variations. PLoS One 9:e102336

Brearley FQ (2013) Nitrogen stable isotopes indicate differences in nitrogen cycling between two contrasting Jamaican montane forests. Plant Soil 367:465–476

Brienen RJW, Wanek W, Hietz P (2011) Stable carbon isotopes in tree rings indicate improved water use efficiency and drought responses of a tropical dry forest tree species. Trees Struct Funct 25:103–113

Brienen GH, Pons TL, Guyot JL, Gloor M (2012) Oxygen isotopes in tree rings are a good proxy for Amazon precipitation and El Niño-Southern oscillation variability. Proc Natl Acad Sci USA 109:16957–16962

Brienen RJW, Hietz P, Wanek W, Gloor M (2013) Oxygen isotopes in tree rings record variation in precipitation $\delta^{18}O$ and amount effects in the south of Mexico. J Geophys Res Biogeosci 118:1604–1615

Brienen RJW, Schöngart J, Zuidema PA (2016) Tree rings in the tropics: insights into the ecology and climate sensitivity of tropical trees. In: Goldstein G, Santiago LS (eds) Tropical tree physiology. Springer, Switzerland, pp 439–461

Brienen RJW, Gloor E, Clerici S, Newton R, Arppe L, Boom A, Bottrell S, Callaghan M, Heaton T, Helama S, Helle G, Leng MJ, Mielikäinen K, Oinonen M, Timonen M (2017) Tree height strongly affects estimates of water-use efficiency responses to climate and CO_2 using isotopes. Nat Commun 8:288

Buchmann N, Guehl JM, Barigah TS, Ehleringer JR (1997) Interseasonal comparison of CO_2 concentrations, isotopic composition, and carbon dynamics in an Amazonian rain forest (French Guiana). Oecologia 110:120–131

Cernusak LA, Winter K, Turner BL (2009) Physiological and isotopic ($\delta^{13}C$ and $\delta^{18}O$) responses of three tropical tree species to water and nutrient availability. Plant Cell Environ 32:1441–1455

Chowdhury M, Schmitz N, Verheyden A, Sass-Klaassen U, Koedam N, Beeckman H (2008) Nature and periodicity of growth rings in two Bangladeshi mangrove species. IAWA J 29:265–276

Cintra BBL, Gloor M, Boom A, Schongart J, Locosselli GM, Brienen R (2019) Contrasting controls on tree ring isotope variation for Amazon floodplain and terra firme trees. Tree Physiol 39:845–860

Colombaroli D, Cherubini P, De Ridder M, Saurer M, Toirambe B, Zweifel N, Beeckman H (2016) Stable carbon and oxygen isotopes in tree rings show physiological responses of *Pericopsis elata* to precipitation in the Congo Basin. J Trop Ecol 32:213–225

Coster C (1927) Zur Anatomie und Physiologie der Zuwachszonen und Jahresbilding in den Tropen. Annales des Jardin Botanique de Buitenzorg 37:49–160

Craven D, Hal JS, Ashton MS, Berlyn GP (2013) Water-use efficiency and whole-plant performance of nine tropical tree species at two sites with contrasting water availability in Panama. Trees 27:639–653

Cullen LE, Grierson PF (2007) A stable oxygen, but not carbon, isotope chronology of *Callitris columellaris* reflects recent climate change in north-western Australia. Clim Chang 85:213–229

Cullen LE, Adams MA, Anderson MJ, Grierson PF (2008) Analyses of $\delta^{13}C$ and $\delta^{18}O$ in tree rings of *Callitris columellaris* provide evidence of a change in stomatal control of photosynthesis in response to regional changes in climate. Tree Physiol 28:1525–1533

Dansgaard W (1964) Stable isotopes in precipitation. Tellus 16:436–468

Ehlers I, Augusti A, Betson TR, Nilsson MB, Marshall JD, Schleucher J (2015) Detecting long-term metabolic shifts using isotopomers: CO_2-driven suppression of photorespiration in C3 plants over the 20th century. Proc Natl Acad Sci USA 112:15585–15590

Ellsworth PZ, Sternberg LSL (2015) Seasonal water use by deciduous and evergreen woody species in a scrub community is based on water availability and root distribution. Ecohydrology 8:538–551

Evans MN, Schrag DP (2004) A stable isotope-based approach to tropical dendroclimatology. Geochim Cosmochim Acta 68:3295–3305

Evans MN (2007) Toward forward modeling for paleoclimatic proxy signal calibration: a case study with oxygen isotopic composition of tropical woods. Geochem Geophys Geosystems 8

Farquhar GD, Ehleringer JR, Hubick KT (1989) Carbon isotope discrimination and photosynthesis. Annu Rev Plant Physiol Plant Mol Biol 40:503–537

Fichtler E, Helle G, Worbes M (2010) Stable-carbon isotope time series from tropical tree rings indicate a precipitation signal. Tree Ring Res 66:35–49

Fu PL, Griessinger J, Gebrekirstos A, Fan ZX, Brauning A (2017) Earlywood and latewood stable carbon and oxygen isotope variations in two pine species in southwestern China during the recent decades. Front Plant Sci 7

Gebrekirstos A, Worbes M, Teketay D, Fetene M, Mitlöhner R (2009) Stable carbon isotope ratios in tree rings of co-occurring species from semi-arid tropics in Africa: patterns and climatic signals. Glob Planet Chang 66:253–260

Gebrekirstos A, van Noordwijk M, Neufeldt H, Mitlöhner R (2011) Relationships of stable carbon isotopes, plant water potential and growth: an approach to asses water use efficiency and growth strategies of dry land agroforestry species. Trees Struct Funct 25:95–102

Guehl JM, Domenach AM, Bereau M, Barigah TS, Casabianca H, Ferhi A, Garbaye J (1998) Functional diversity in an Amazonian rainforest of French Guyana: a dual isotope approach ($\delta^{15}N$ and $\delta^{13}C$). Oecologia 116:316–330

Hasselquist NJ, Allen MF, Santiago LS (2010) Water relations of evergreen and drought-deciduous trees along a seasonally dry tropical forest chronosequence. Oecologia 164:881–890

Helle G, Schleser GH (2004) Beyond CO_2-fixation by Rubisco—an interpretation of $^{13}C/^{12}C$ variations in tree rings from novel intra-seasonal studies on broad-leaf trees. Plant Cell Environ 27:367–380

Hietz P, Wanek W, Dünisch O (2005) Long-term trends in cellulose $\delta^{13}C$ and water-use efficiency of tropical *Cedrela* and *Swietenia* from Brazil. Tree Physiol 25:745–752

Hietz P, Dünisch O, Wanek W (2010) Long-term trends in nitrogen isotope composition and nitrogen concentration in Brazilian rainforest trees suggest changes in nitrogen cycle. Environ Sci Technol 44:1191–1196

Hietz P, Turner BL, Wanek W, Richter A, Nock CA, Wright SJ (2011) Long-term change in the nitrogen cycle of tropical forests. Science 334:664–666

Jackson PC, Cavelier J, Goldstein G, Meinzer FC, Holbrook NM (1995) Partitioning of water-resources among plants of a lowland tropical forest. Oecologia 101:197–203

Kagawa A, Sugimoto A, Maximov TC (2006) $^{13}CO_2$ pulse-labelling of photoassimilates reveals carbon allocation within and between tree rings. Plant Cell Environ 29:1571–1584

Körner C (2009) Responses of humid tropical trees to rising CO_2. Annu Rev Ecol Evol Syst 40:61–79

Krepkowski J, Gebrekirstos A, Shibistova O, Brauning A (2013) Stable carbon isotope labeling reveals different carry-over effects between functional types of tropical trees in an Ethiopian mountain forest. New Phytol 199:431–440

Kricher J (2011) Tropical ecology. Princeton University Press, Princeton and Oxford

Kurita N, Ichiyanagi K, Matsumoto J, Yamanaka MD, Ohata T (2009) The relationship between the isotopic content of precipitation and the precipitation amount in tropical regions. J Geochem Explor 102:113–122

Lambers H, Chapin FS III, Pons TL (2008) Plant physiological ecology. Springer, New York

Leavitt SW, Long A (1991) Seasonal stable isotope variability in tree rings—possible paleoenvironmental signals. Chem Geol 87:59–70

Loader NJ, Walsh RPD, Robertson I, Bidin K, Ong RC, Reynolds G, McCarroll D, Gagen M, Young GHF (2011) Recent trends in the intrinsic water-use efficiency of ringless rainforest trees in Borneo. Philos Trans R Soc B Biol Sci 366:3330–3339

Locosselli GM, Buckeridge MS, Moreira MZ, Ceccantini G (2013) A multi-proxy dendroecological analysis of two tropical species *(Hymenaea* spp., Leguminosae) growing in a vegetation mosaic. Trees Struct Funct 27:25–36

Managave S, Sheshshayee M, Borgaonkar H, Ramesh R (2010) Past break-monsoon conditions detectable by high resolution intra-annual δ^{18}O analysis of teak rings. Geophys Res Lett 37:L05702

Managave SR, Sheshshayee MS, Ramesh R, Borgaonkar HP, Shah SK, Bhattacharyya A (2011) Response of cellulose oxygen isotope values of teak trees in differing monsoon environments to monsoon rainfall. Dendrochronologia 29:89–97

Managave S, Sheshshayee M, Bhattacharyya A, Ramesh R (2011) Intra-annual variations of teak cellulose δ^{18}O in Kerala, India: implications to the reconstruction of past summer and winter monsoon rains. Clim Dyn 37:555–567

Managave SR, Shimla P, Borgaonkar HP, Bhattacharyya A, Ramesh R (2017) Regional differences in the carbon isotopic compositions of teak from two monsoonal regimes of India. Dendrochronologia 44:203–210

Martinelli LA, Piccolo MC, Townsend AR, Vitousek PM, Cuevas E, McDowell W, Robertson GP, Santos OC, Treseder K (1999) Nitrogen stable isotopic composition of leaves and soil: tropical versus temperate forests. Biogeochemistry 46:45–65

Medina E, Minchin P (1980) Stratification of δ^{13}C values of leaves in Amazonian rainforests. Oecologia 45:377–378

Medina E, Sternberg L, Cuevas E (1991) Vertical stratification of ^{13}C values in closed natural and plantation forests in the Luquillo mountains, Puerto Rico. Oecologia 87:369–372

Menge DNL, Chazdon RL (2016) Higher survival drives the success of nitrogen-fixing trees through succession in Costa Rican rainforests. New Phytol 209:965–977

Menge DNL, Levin SA, Hedin LO (2009) Facultative versus obligate nitrogen fixation strategies and their ecosystem consequences. Am Nat 174:465–477

Mokria M, Gebrekirstos A, Abiyu A, Brauning A (2018) Upper Nile River flow reconstructed to AD 1784 from tree-rings for a long-term perspective on hydrologic-extremes and effective water resource management. Quat Sci Rev 199:126–143

Nock CA, Baker PJ, Wanek W, Leis A, Grabner M, Bunyavejchewin S, Hietz P (2011) Long-term increases in intrinsic water-use efficiency do not lead to increased stem growth in a tropical monsoon forest in western Thailand. Glob Chang Biol 17:1049–1063

Ohashi S, Durgante FM, Kagawa A, Kajimoto T, Trumbore SE, Xu X, Ishizuka M, Higuchi N (2016) Seasonal variations in the stable oxygen isotope ratio of wood cellulose reveal annual rings of trees in a Central Amazon terra firme forest. Oecologia 180:685–696

Ohashi S, Okada N, Nobuchi T, Siripatanadilok S, Veenin T (2009) Detecting invisible growth rings of trees in seasonally dry forests in Thailand: isotopic and wood anatomical approaches. Trees Struct Funct 23:813–822

Pons TL, Helle G (2011) Identification of anatomically non-distinct annual rings in tropical trees using stable isotopes. Trees Struct Funct 25:83–93

Pons TL, Alexander EE, Houter NC, Rose SA, Rijkers T (2005) Ecophysiological patterns in Guianan forest plants. In: Hammond DS (ed) Tropical forests of the Guiana shield; Ancient forests in a Modern World. CABI Publishing, Wallingford, UK, pp 195–231

Pons TL, Perreijn K, Van Kessel C, Werger MJA (2007) Symbiotic nitrogen fixation in a tropical rainforest: ^{15}N natural abundance measurements supported by experimental isotopic enrichment. New Phytol 173:154–167

Poussart PF, Schrag DP (2005) Seasonally resolved stable isotope chronologies from northern Thailand deciduous trees. Earth Planet Sci Lett 235:752–765

Poussart PF, Evans MN, Schrag DP (2004) Resolving seasonality in tropical trees: multi-decade, high-resolution oxygen and carbon isotope records from Indonesia and Thailand. Earth Planet Sci Lett 218:301–316

Pumijumnong N, Brauning A, Sano M, Nakatsuka T, Muangsong C, Buajan S (2020) A 338-year tree-ring oxygen isotope record from Thai teak captures the variations in the Asian summer monsoon system. Sci Rep 10

Rahman M, Islam M, Gebrekirstos A, Bräuning A (2020) Disentangling the effects of atmospheric CO_2 and climate on intrinsic water-use efficiency variability in South Asian tropical moist forest trees. Tree Physiol 40:904–916

Roggy JC, Prévost MF, Gourbiere F, Casabianca H, Garbaye J, Domenach AM (1999) Leaf natural ^{15}N abundance and total N concentration as potential indicators of plant N nutrition in legumes and pioneer species in a rain forest of French Guiana. Oecologia 120:171–182

Rozendaal DMA, Zuidema PA (2011) Dendroecology in the tropics: a review. Trees Struct Funct 25:3–16

Sano M, Xu CX, Nakatsuka T (2012) A 300-year Vietnam hydroclimate and ENSO variability record reconstructed from tree ring $\delta^{18}O$. J Geophys Res Atmos 117

Scheidegger Y, Saurer M, Bahn M, Siegwolf R (2000) Linking stable oxygen and carbon isotopes with stomatal conductance and photosynthetic capacity: a conceptual model. Oecologia 125:350–357

Schollaen K, Heinrich I, Neuwirth B, Krusic PJ, D'Arrigo RD, Karyanto O, Helle G (2013) Multiple tree-ring chronologies (ring width, $\delta^{13}C$ and $\delta^{18}O$) reveal dry and rainy season signals of rainfall in Indonesia. Quat Sci Rev 73:170–181

Schollaen K, Karamperidou C, Krusic P, Cook E, Helle G (2015) ENSO flavors in a tree-ring $\delta^{18}O$ record of *Tectona grandis* from Indonesia. Clim Past 11:1325–1333

Schöngart J, Piedade MTF, Ludwigshausen S, Horna V, Worbes M (2002) Phenology and stem-growth periodicity of tree species in Amazonian floodplain forests. J Trop Ecol 18:581–597

Schöngart J, Bräuning A, Maioli Campos Barbosa AC, Lisi CS, Morales de Oliveira J (2017) Dendroecological studies in the neotropics: history, status and future challenges. In: Amoroso MM, Daniels LD, Baker PJ, Camarero JJ (eds) Dendroecology—tree-ring analyses applied to ecological studies. Springer International Publishing, Switzerland

Schubert BA, Timmermann A (2015) Reconstruction of seasonal precipitation in Hawaï using high-resolution carbon isotope measurements across tree rings. Chem Geol 417:273–278

Schwendenmann L, Pendall E, Sanchez-Bragado R, Kunert N, Hoelscher D (2015) Tree water uptake in a tropical plantation varying in tree diversity: interspecific differences, seasonal shifts and complementarity. Ecohydrology 8:1–12

Silva LCR, Anand M (2013) Probing for the influence of atmospheric CO_2 and climate change on forest ecosystems across biomes. Glob Ecol Biogeogr 22:83–92

Stahl C, Herault B, Rossi V, Burban B, Brechet C, Bonal D (2013) Depth of soil water uptake by tropical rainforest trees during dry periods: does tree dimension matter? Oecologia 173:1191–1201

Sternberg LSLO (2009) Oxygen stable isotope ratios in tree-ring cellulose: the next phase of understanding. New Phytol 181:553–562

Sturm C, Hoffmann G, Langmann B (2007) Simulation of the stable water isotopes in precipitation over South America: comparing regional to global circulation models. J Clim 20:3730–3750

Thompson LG, Mosley-Thompson E, Brecher H, Davis M, León B, Les D, Lin PN, Mashiotta T, Mountain K (2006) Abrupt tropical climate change: past and present. Proc Natl Acad Sci USA 103:10536–10543

van der Sleen P, Soliz-Gamboa CC, Helle G, Pons TL, Anten NPR, Zuidema PA (2014) Understanding causes of tree growth response to gap formation: $\Delta^{13}C$-values in tree rings reveal a predominant effect of light. Trees Struct Funct 28:439–448

van der Sleen P, Vlam M, Groenendijk P, Anten NPR, Bongers F, Bunyavejchewin S, Hietz P, Pons TL, Zuidema PA (2015) ^{15}N in tree rings as a bio-indicator of changing nitrogen cycling in tropical forests: an evaluation at three sites using two sampling methods. Front Plant Sci 6:229

van der Sleen P, Groenendijk P, Zuidema PA (2015) Tree-ring δ^{18}O in African mahogany (E*ntandrophragma utile*) records regional precipitation and can be used for climate reconstructions. Glob Planet Chang 127:58–66

van der Sleen P, Groenendijk P, Vlam M, Anten NPR, Boom A, Bongers F, Pons TL, Terburg G, Zuidema PA (2015) No growth stimulation of tropical trees by 150 years of CO_2 fertilization but water-use efficiency increased. Nat Geosci 8:24–28

van der Sleen P, Zuidema PA, Pons TL (2017) Stable isotopes in tropical tree rings: theory, methods and applications. Funct Ecol 31:1674–1689

van der Sleen P (2014) Environmental and physiological drivers of tree growth. Wageningen University, the Netherlands

Verheyden A, Helle G, Schleser GH, Dehairs F, Beeckman H, Koedam N (2004) Annual cyclicity in high-resolution stable carbon and oxygen isotope ratios in the wood of the mangrove tree *Rhizophora mucronata.* Plant Cell Environ 27:1525–1536

Villacıs M, Vimeux F, Taupin JD (2008) Analysis of the climate controls on the isotopic composition of precipitation (δ^{18}O) at Nuevo Rocafuerte, 74.5°W, 0.9°S, 250 m Ecuador. Comptes Rendus Geosci 340:1–9

Vitousek PM, Howarth RW (1991) Nitrogen limitation on land and in the sea: how can it occur? Biogeochemistry 13:87–115

Vlam M, Baker PJ, Bunyavejchewin S, Zuidema PA (2014) Temperature and rainfall strongly drive temporal growth variation in Asian tropical forest trees. Oecologia 174:1449–1461

Vlam M, de Groot GA, Boom A, Copinid P, Larosb I, Veldhuijzena K, Zakamdie D, Zuidema PA (2018) Developing forensic tools for an African timber: regional origin is revealed by genetic characteristics, but not by isotopic signature. Biol Cons 220:262–271

Volland F, Pucha D, Bräuning A (2016) Hydro-climatic variability in southern Ecuador reflected by tree-ring oxygen isotopes. Erdkunde 70:69–82

Waterhouse JS, Cheng SY, Juchelka D, Loader NJ, McCarroll D, Switsur VR, Gautam L (2013) Position-specific measurement of oxygen isotope ratios in cellulose: isotopic exchange during heterotrophic cellulose synthesis. Geochim Cosmochim Acta 112:178–191

Wils THG, Robertson I, Eshetu Z, Koprowski M, Sass-Klaassen UGW, Touchan R, Loader NJ (2010) Towards a reconstruction of Blue Nile baseflow from Ethiopian tree rings. Holocene 20:837–848

Worbes M (2002) One hundred years of tree-ring research in the tropics—a brief history and an outlook to future challenges. Dendrochronologia 20:217–231

Xu C, Sano M, Nakatsuka T (2011) Tree ring cellulose δ^{18}O of *Fokienia hodginsii* in northern Laos: a promising proxy to reconstruct ENSO? J Geophys Res D Atmos 116:D24109

Xu CX, Sano M, Yoshimura K, Nakatsuka T (2014) Oxygen isotopes as a valuable tool for measuring annual growth in tropical trees that lack distinct annual rings. Geochem J 48:371–378

Xu CX, Pumijumnong N, Nakatsuka T, Sano M, Li Z (2015) A tree-ring cellulose δ^{18}O-based July–October precipitation reconstruction since AD 1828, northwest Thailand. J Hydrol 529:433–441

Xu C, Sano M, Nakatsuka T (2013) A 400-year record of hydroclimate variability and local ENSO history in northern Southeast Asia inferred from tree-ring δ^{18}O. Palaeogeogr Palaeoclim Palaeoecol 386:588–598

Zhu M, Stott L, Buckley B, Yoshimura K (2012) 20th century seasonal moisture balance in Southeast Asian montane forests from tree cellulose δ^{18}O. Clim Chang 115:505–517

Zhu MF, Stott L, Buckley B, Yoshimura K, Ra K (2012b) Indo-Pacific Warm Pool convection and ENSO since 1867 derived from Cambodian pine tree cellulose oxygen isotopes. J Geophys Res Atmos 117

Zuidema PA, Brienen RJW, Schöngart J (2012) Tropical forest warming: looking backwards for more insights. Trends Ecol Evol 27:193–194

Zuidema PA, Poulter B, Frank DC (2018) A wood biology agenda to support global vegetation modelling. Trends Plant Sci 23:1006–1015