**Title:** Thermal sensitivity across forest vertical profiles: patterns, mechanisms, and ecological implications

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| --- | --- | --- | --- |
| Text | word count | other | n |
| Total word count (excluding summary, references and legends) | 8565 | No. of figures | 6 (all colour) |
| Summary | 183 | No. of Tables | 2 |
| Introduction | 495 | No of Supporting Information files | 6 |
| Review of vertical gradients | 5976 |  |  |
| Implications | 1753 |  |  |
| Conclusions | 156 |  |  |
| Acknowledgments | ## |  |  |

## Summary

Rising temperatures are profoundly influencing forests on many scales with potentially strong variation vertically across forest strata. Using published research and new analyses, we evaluate how environmental conditions, leaf temperatures, and foliar traits and metabolism vary across vertical gradients, shaping whole-tree ecology and ecosystem function. In forests with dense canopies, canopy leaves are exposed to higher solar radiation and evaporative demand than understory leaves, and can experience elevated leaf temperature (), particularly when transpirational cooling is curtailed by limited stomatal conductance. However, foliar traits that also vary strongly across height or light gradients can partially mitigate the elevation of in the upper canopy. Leaf metabolism generally increases with height across the vertical gradient, and tall trees have higher absolute metabolic capacity and growth at both individual and ecosystem levels. Yet, differences in thermal sensitivity and damage thresholds across the gradient are modest. Under climate warming and increased drought, larger trees can face disproportionate stress, yet understory trees have fewer cooling mechanisms and thus may be impacted the most under hot, humid conditions, or when the buffering provided by large trees is lost.

# Introduction

Forest responses and feedbacks to climate change will have a critical influence on the future of Earth’s climate. Global average temperatures have risen 1.2 C since 1900 (Rohde & Hausfather, 2020) and are expected to reach or even exceed +1.5 C in the next 20 years (IPCC, 2021), accompanied by increasing severity and frequency of heat waves (Meehl & Tebaldi, 2004; IPCC, 2021) and hotter droughts (Trenberth *et al.*, 2014). These changes are expected to have profound effects on tree metabolism and forest ecosystem function (Breshears *et al.*, 2021; Pörtner *et al.*, 2021) by altering rates of photosynthesis and respiration (Corlett, 2011; Breshears *et al.*, 2021; Scafaro *et al.*, 2021), causing foliar damage during heat waves (Corlett, 2011; O’Sullivan *et al.*, 2017), and reducing growth and elevating mortality during drought (McDowell *et al.*, 2020; Breshears *et al.*, 2021). The net result of higher temperatures may be increased or decreased tree growth and forest carbon sequestration, with decreases being more commonly documented across the world’s forests (Oishi *et al.*, 2018; Sullivan *et al.*, 2020; **Anderson-TeixeiraJointEffectsClimate2021?**). The resulting feedbacks to the climate system, carbon storage, and changes in albedo and hydrology will in turn impact the the future trajectory of climate change (Bonan, 2016), yet the degree of the impact remains uncertain (Friedlingstein *et al.*, 2006; Krause *et al.*, 2018).

A great measure of uncertainty arises due to the differential impacts of rising temperatures on trees of differential size and canopy position, especially as small understory trees exist in microenvironments that are substantially buffered by more exposed canopy trees (Davis *et al.*, 2019a; Zellweger *et al.*, 2019). Forests are vertically and horizontally stratified, with overstory canopies playing a crucial role in moderating forest climatic conditions (Ozanne *et al.*, 2003; Nakamura *et al.*, 2017), including buffering understory microclimates from extreme meteorological conditions (Zellweger *et al.*, 2019). This creates a vertical stratification of the biophysical environment such as temperature, light, wind, humidity and CO2 concentrations that influences leaf traits, thermoregulation and metabolism along the gradient, with implications for whole plant performance (Michaletz *et al.*, 2016; Fauset *et al.*, 2018). Despite the fact that this vertical gradient inevitably shapes nearly every aspect of plant metabolism, demography, and ecology, we lack comprehensive understanding of these gradients (but see Niinemets & Valladares, 2004). Importantly, this limits our ability to understand how warming temperatures will affect leaf-level metabolism, whole-plant performance, and, in turn, forest ecosystem dynamics, biodiversity, energy balance, ecosystem function, and biosphere-atmosphere interactions.

Here, we review how the biophysical environment and plant form and function vary across the vertical canopy gradient in forests. We focus on five key themes (Fig. 1): (1) the biophysical environment; (2) leaf temperature (); (3) the leaf traits that most strongly influence ; (4) leaf metabolism and gas exchange, including stomatal conductance, photosynthesis, respiration, and volatile organic compound (VOC) production; and (5) whole-tree and ecosystem ecology. We then consider the implications for understanding forest responses to global change, including how these responses scale across space and time.



**Figure 1. Schematic summarizing vertical gradients in forests according to (1) biophysical environment, (2) leaf temperature (), (3) leaf traits, (4) leaf metabolism, and (5) whole-tree and ecosystem ecology.** Abbreviations are as follows: VPD: vapor pressure deficit; - : leaf-to-air temperature difference; LMA: leaf mass per area, VAZ: violaxanthin, antheraxanthin and zeaxanthin concentrations, VOC: volatile organic compounds; T sensitivity: temperature sensitivity; ET: evapotranspiration. Here, we summarize conditions in dense canopies during growing season and daytime conditions; patterns tend to be weaker, or sometimes reversed, in more open canopies, when canopy trees are seasonally deciduous, or at nighttime. Arrows indicate direction of increase, with double-pointed arrows indicating that observations have shown increases both higher and lower in the canopy.

# Review of vertical gradients

## The biophysical environment

**The biophysical environment, defined here to include the physical structure of the vegetation and associated physical conditions, varies across the vertical gradient from the forest floor to the top of the canopy (Figs. 1, 2), with physical conditions in large part determined by the structure of the forest.** In this section, we supplement a review of the existing literature with a new analysis of data on vegetation structure and vertical microclimate profiles from focal sites within the U.S. National Ecological Observatory Network (NEON; Fig. 2, Supporting Information Figure S1; Supporting Information Methods S1, Schimel *et al.*, 2007). While the focus here is on vertical gradients, it is important to note that in heterogeneous canopies with high gap fractions and large variation in tree height, or at forest edges, the biophysical environment can be more closely linked to the distance from the outer canopy than to height (Lowman & Rinker, 1995).



**Figure 2. Vertical gradients in the biophysical environment for six US forest sites with contrasting forest structures in the National Ecological Observatory Network (NEON)**. Height profiles from the growing season are shown for: (a) leaf area density, (b) proportion of sun leaves, (c) proportion light incident at the top of the canopy, and July mean ± 1 standard deviation for (d) maximum photosynthetically active radiation (PAR), (e) maximum wind speed, (f) minimum humidity, (g) maximum , and (h) maximum biological temperature, . Sites include a mixed northern hardwood and coniferous forest (Harvard Forest, MA; HARV), a subtropical longleaf pine savanna (Ordway-Swisher Biological Station, FL; OSBS), a tropical montane broadleaf evergreen forest (Pu’u Maka’ala Natural Area Reserve, Hawai’i; PUUM), two temperate broadleaf forests (Smithsonian Conservation Biology Institute, VA, SCBI; Smithsonian Environmental Research Center, MD, SERC), and a coniferous forest (Wind River Experimental Forests, WA; WREF). Vertical profiles in micrometeorological variables (d-h) at all six NEON sites are shown in Supporting Information Figure S1. Further site information is given in Supporting Information Table S1, and analysis details in Supporting Information Methods S1.

**Canopy foliage acts as the primary physical barrier between the atmosphere and the forest floor, buffering multiple aspects of the understory conditions. It is critical in influencing – and is influenced by – the vertical biophysical gradient (Fig. 2).** Foliage distribution within a forest is determined by the distribution of tree sizes and tree architecture, along the vertical gradient by leaf area density (LAD; *i.e.*, leaf area per unit volume) patterns that are heterogeneous across forests (Fig. 2a-b, Supporting Information Figure S1). Dense canopy forests composed of broadleaf trees can have high LAD in the upper canopy layers, as well as in the understory (e.g., SCBI, SERC and HARV, Fig. 2a) – a pattern also common in tropical forests (Ashton & Hall, 1992; Koike & Syahbuddin, 1993). In temperate forests, although LAD is generally more concentrated in the upper-canopy, undualting patterns are formed by conifers and top- vs. bottom-heavy foliage trees, and sometimes by dense understories (Terborgh, 1985; e.g., SCBI, Fig. 2a, Parker *et al.*, 1989, 2002; Ishii *et al.*, 2004). In forests with more open upper canopies, including many needle-leaf forests, LAD can be predominantly accumulated in the lower canopy or understory layers (Baldocchi *et al.*, 1997; Law *et al.*, 2001; Ishii *et al.*, 2004; Bonan, 2016; e.g., OSBS, PUUM, and WREF, Fig. 2a, Hanberry *et al.*, 2020). Soil moisture conditions, topography, and gap formations following disturbances all alter foliage patterns (Bonan, 2016; e.g., Almeida *et al.*, 2016; Stark *et al.*, 2020; Hanberry *et al.*, 2020). In addition, seasonally dry and wet conditions, deciduousness, and phenology contribute to temporally shifting LAD patterns (Parker & Tibbs, 2004; Parker *et al.*, 2019). In this review, we focus on growing season conditions (peak leaf area index, LAI) unless otherwise noted.

**Light, specifically the proportion of incident light and photosynthetically active radiation (PAR), decreases from the canopy top to the forest floor, with the profile shape modified by LAD, canopy height, canopy structure, and across species and forest types (Fig. 2a-d, Supporting Information Figure S1, Koike *et al.*, 2001).** This gradient is more pronounced in dense canopies, including broad-leaf and mixed forests (e.g., SCBI, SERC and HARV, Fig. 2d), than in open canopy forests, including many conifer forests (Chazdon & Fetcher, 1984; Baldocchi *et al.*, 1997; e.g., OSBS, PUUM, and WREF, Fig. 2d, Supporting Information Figure S1, Aussenac, 2000; Bartemucci *et al.*, 2006; Tymen *et al.*, 2017; Smith *et al.*, 2019b; Parker *et al.*, 2019). Variability in the light environment decreases with height, with the shaded understory being highly influenced by sunflecks, or brief increases in solar radiation caused by small canopy gaps and wind-induced canopy movements (Way & Pearcy, 2012).

**Wind speeds are also higher at the top of the canopy, owing to the buffering effect of the canopy (Jucker *et al.*, 2018).** Wind speeds increase with height across forest types [Fig. 2e, Supporting Information Figure S1; Barnard & Bauerle (2016); McGregor *et al.* (2021); Jucker *et al.* (2018); Muller *et al.* (2021); Hanberry *et al.* (2020); Hanberry *et al.* (2018)] and savannas (Curtis *et al.*, 2019; Johnston *et al.*, 2020). Specifically, averaged across the NEON sites, maximum daily wind speeds were 4.1 m s-1 at the top of the vertical profile, compared to 1.1 m s-1 at the bottom (Fig. 2, Supporting Information Figure S1). The implication is that upper canopy leaves have substantially higher boundary layer conductance () and therefore greater potential for both water and heat loss (see section “Leaf temperature”).

**Atmospheric concentrations of carbon dioxide (CO2) and water vapor can also vary across the vertical gradient.** Atmospheric CO2 concentrations tend to be higher near the ground at night, associated with plant and soil respiration, although the elevated CO2 quickly dissipates during the day (Yang *et al.*, 1999; Koike *et al.*, 2001). Elevated CO2 may benefit understory seedlings operating close to their carbon compensation point, but given that differences are negligible for most of the day when photosynthesis is occurring, gradients in CO2 concentrations are unlikely to significantly affect the energy balance and metabolism of leaves across the forest vertical gradient.

Relative humidity (RH) tends to be higher in the understory and decreases with height, although this trend is absent in open forests (Jucker *et al.*, 2018; Fig. 2f, Supporting Information Figure S1, e.g., McGregor *et al.*, 2021). Dense-canopy forests maintain higher daily maximum RH in the understory than open forests and nearby open areas, an effect that is greater in wetter conditions, and warmer months (von Arx *et al.*, 2012; Hanberry *et al.*, 2020). In combination with , RH determines vapor pressure deficit (VPD) – the driving force of water loss from leaves, which tends to be greater in the upper canopy and canopy gaps than in the understory (Niinemets & Valladares, 2004; Tymen *et al.*, 2017; Fauset *et al.*, 2018). Especially when canopy height and LAI are large, maximum and VPD are reduced in the understory (Jucker *et al.*, 2018).

**Air temperature () often shows little variation across the vertical gradient, but under certain circumstances it can be significantly buffered by forest canopies (Fig. 2, Supporting Information Figure S1).** The gradient from the upper canopy to the understory varies with factors such as radiation fluxes, local topography, vertical air mixing, cloud cover and vegetation type (De Frenne *et al.*, 2021). Typically, dense canopies buffer understories from high maximum more than open canopies – *i.e.*, dense canopy understories can have cooler maximum daytime and warmer nighttime minimum than open canopy understories or nearby clearings (Misson *et al.*, 2007; Rambo & North, 2009; von Arx *et al.*, 2012; Davis *et al.*, 2019a; De Frenne *et al.*, 2019, 2021; Zellweger *et al.*, 2019). Notably, this pattern can be reversed in open forests, where below-canopy maximum can be warmer than canopy due to turbulent air mixing and the thermal radiative flux from the soil and the canopy that is intercepted by lower-canopy layers, analogous to a ‘canopy greenhouse effect’ (Hadley & Smith, 1987; Zweifel *et al.*, 2002; Rambo & North, 2009; Hardwick *et al.*, 2015; e.g., OSBS, Fig. 2g, Supporting Information Figure S1b, Banerjee *et al.*, 2017; Curtis *et al.*, 2019).

## Leaf temperature

Leaf temperature () is strongly tied to , and is further influenced by other biophysical drivers (reviewed above) and by leaf traits and stomatal conductance (see following sections) with leaves adjusting to their environment to approach, when possible, an optimal for carbon assimilation and metabolic processes (Michaletz *et al.*, 2015; Drake *et al.*, 2020; Perez & Feeley, 2020). Leaves are typically cooler than the air at night, and during the day especially under cloudy skies, at high windspeeds and high . Leaves are typically warmer than air when under full sunlight, especially under slow windspeeds and low (Doughty & Goulden, 2008). While is rarely exactly equal to , it is most commonly within a few degrees (Cavaleri, 2020).

### Biophysical drivers

**Fundamentally, is determined by the energy balance of a leaf and can be estimated based on biophysical principles, where is a function of energy input from net radiation (, including shortwave and longwave) minus heat lost to the environment (Fig. 3, Campbell & Norman, 1998; Muir, 2019).** High loads can elevate dramatically above (Fig. 3a). Sensible heat flux between leaf and air is regulated by leaf boundary layer conductance, which is greater in smaller leaves (Fig. 3d) and higher wind speeds (Fig. 3b). Latent heat flux () through transpiration has a strong cooling effect, and is determined by stomatal and boundary layer conductances ( and ) and VPD; notably, is influenced by windspeed and respond due to stomatal closure under high VPD. Therefore, under full sunlight, decreases with , which increases with wind speed (Fig. 3b, Daudet *et al.*, 1999) and (Fig. 3e); increases with leaf size (Fig. 3d); and increases with RH (Fig. 3c).



**Figure 3. Theoretical expectations for variation in in response to (a) shortwave radiation, (b) wind speed, (c) relative humidity, (d) leaf width, and (e) stomatal conductance.** Leaf temperatures were modeled using the tealeaves R package of Muir (2019) parameterized to represent typical conditions for a broadleaf species (*Quercus rubra* L.) in a mesic temperate forest (Harvard Forest, Massachusetts, USA), as detailed in Supplementary Information Methods S2. Model parameters for biophysical conditions are given in Supplementary Information Table S2.

**Leaf energy balance is a tradeoff between water uptake and optimum (Koch *et al.*, 1994; Fauset *et al.*, 2018).** When is high, high facilitates heat dissipation. However, when leaf water demand (influenced by VPD and stomatal opening) exceeds the rate of supply, conservation of water (-limitation) occurs at the cost of increasing (Fig. 3e, Fauset *et al.*, 2018). Therefore, while under maximum , leaves can maintain closer to at high solar radiation loads, but during -limitation solar radiation can drastically elevate above , especially for larger leaves (Fauset *et al.*, 2018; Song *et al.*, 2020; Konrad *et al.*, 2021). With adequate water, species with smaller leaves (higher ) and larger will be most effective at cooling under high temperatures (Leuzinger & Körner, 2007; Dong *et al.*, 2017; Leigh *et al.*, 2017; Song *et al.*, 2020; Konrad *et al.*, 2021).

**Vertical gradients**

**These basic biophysical principles shape the tendency for to be elevated above across vertical gradients in closed-canopy forests.** High radiation at the top of the vertical profile (Fig. 2) implies that canopy leaves have much greater tendency for high , such that they would be expected to be warmer than understory leaves under most conditions (Fig. 3). However, higher wind speeds (e.g., ~ 4 ; Fig. 2) can reduce to ~ C (Niinemets & Valladares, 2004; Fig. 3b, Bonan, 2016). Collectively, higher wind speed (Fig. 2), and with adaptive leaf traits increase and (reviewed below) mediate the direct effects of solar radiation on upper canopy leaves (Fig. 3a) and result in higher rates of heat loss (Fig. 3b-e). In contrast, greater RH and lower wind speeds in the understory may limit (through reduced and ), thereby increasing (Tibbitts, 1979; Fig. 3, Perez & Feeley, 2018).

**Vertical gradients are also expected to vary with canopy structure (Fig. 3).** Closed canopies with high LAI act as an parasol, absorbing most of the incoming radiation and preventing vertical air mixing in the understory. In contrast to closed canopies, open canopies with lower LAI allow more vertical air mixing and sunlight into the understory. This mixing and light penetration can either neutralize a gradient or elevate in the lower canopy relative to the upper canopy. The latter can result from the ‘canopy greenhouse effect’ or sunflecks, as mentioned above (Schymanski *et al.*, 2013; Hardwick *et al.*, 2015), and because shade leaves tend to have lower and greater thermal capacitance (capacity to hold heat, Schymanski *et al.*, 2013).

**Within closed-canopy forests vertical gradients, the propensity for to be elevated above varies with micrometeorological conditions (Fig. 3).** Under drought conditions (hot and dry, with higher-than-average solar radiation), when is limiting, there will be a propensity for to be elevated in the canopy compared to the understory (Fig.3). Because sun leaves are exposed to higher irradiance and VPD, their -limitation is steeper than shade leaves, resulting in greater increases in when is reduced (Fig. 3e, Leigh *et al.*, 2017; Fauset *et al.*, 2018). In contrast, under hot and wet conditions, higher wind speeds and enable cooling. Under lower wind conditions, however, lower increases (Roberts *et al.*, 1990a; Fig. 3b, Martin *et al.*, 1999; Leigh *et al.*, 2017; Song *et al.*, 2020). Thus, while understory and within-canopy shade leaves can remain cooler under lower radiation, their environment is not conducive to shedding excess heat, which in combination with their physiological propensities can result in greater under slight heat stress (Zweifel *et al.*, 2002; Schymanski *et al.*, 2013; Leigh *et al.*, 2017; Song *et al.*, 2020). In addition to lower wind speeds (Fig. 2), higher RH in the understory (Fig. 2) would also inhibit cooling, as is stifled under high RH, resulting in greater - (Tibbitts, 1979; Perez & Feeley, 2018; Fig. 3c, Song *et al.*, 2020; Konrad *et al.*, 2021).

### In situ observations

**Following the principles outlined above, vertical microclimate profiles, leaf traits, and together explain *in situ* observations.** Often, tracks , *in large part due to vertical gradients in leaf traits and ,* and therefore differs little between understory and canopy. In forests with dense canopies, including tropical and temperate broadleaf forests, leaves experience greater and higher maximum in the upper canopy than buffered lower-canopies. In some cases canopy leaves exceed the optima for photosynthesis () and because of -limitation and high solar radiation loads (Niinemets *et al.*, 1999; Doughty & Goulden, 2008; Rey-Sánchez *et al.*, 2016; Fauset *et al.*, 2018; Pau *et al.*, 2018; Mau *et al.*, 2018; Carter *et al.*, 2021; Miller *et al.*, 2021). In contrast, in open forests with lower LAI, lower-canopy can equal or even exceed upper canopy , due to greater light transmission, vertical air mixing, and still air in the lower canopy and heating from the ground (Hadley & Smith, 1987; Martin *et al.*, 1999; Zweifel *et al.*, 2002; Fig. 2h, Supporting Information Figure S1b,e, Muller *et al.*, 2021). Similarly, in very open forests or savannas, trees growing close to the ground can experience greater heat stress in their lower than upper canopies (Hadley & Smith, 1987; Curtis *et al.*, 2019; Johnston *et al.*, 2020). Greater in the inner canopy can also increase relative to upper canopy (Dietz *et al.*, 2007).

## Leaf traits

**Leaf traits determine the capacity of leaves to thermoregulate (Michaletz *et al.*, 2016), and as such are critical to optimizing leaf metabolism across forest vertical strata (Zwieniecki *et al.*, 2004; Michaletz *et al.*, 2015).** Leaf morphology adjusts to the previously experienced microenvironment during leaf formation in buds, and also during ongoing leaf expansion (Zwieniecki *et al.*, 2004), and the ratio of far red to red light and associated water demands determines the differentiation of traits of sun and shade leaves (Zwieniecki *et al.*, 2004; Casas *et al.*, 2011; Keenan & Niinemets, 2016). This dichotomy in leaves is observed along the vertical gradient where canopy-leaves vary dramatically from canopy-interior and understory due to the differences in biophysical conditions (Fig. 2, Supporting Information Figure S1).

Across the vertical gradient, traits vary (1) across sun and shade leaves within individuals, (2) across canopy and understory individuals of the same species, and (3) across canopy and understory species. The majority of studies characterizing variation in leaf traits or metabolism examine intraspecific patterns (categories 1 and 2), which are therefore the main focus of this review (Table 1). However, when it comes to understanding and modeling forest ecosystem function, given that species traits strongly shape the propensity for trees to inhabit understory vs. canopy positions, ecosystem function is also shaped by interspecific trait variation [e.g., *Lamour, Serbin in prep*; Cavaleri *et al.* (2010)].

### Intraspecific variation

Within-canopy, leaf traits vary along the vertical light gradient (*i.e.,* sun and shade leaves, Casas *et al.*, 2011) at a biochemical, anatomical and structural level (Table 1, Sack *et al.*, 2006; Niinemets *et al.*, 2015a; Chen *et al.*, 2020). As much of our understanding of trait coordination is based on the leaf economics spectrum concept developed across diverse species (Wright *et al.*, 2004) which was developed using sun leaves (Keenan & Niinemets, 2016; Chen *et al.*, 2020), further research is needed to characterize trait relationships and responses vertically through the full range of canopy microenvironments. It has been established that independently of the light environment, traits also vary within species along the ontogenetic trajectory from the understory to the canopy. For example, leaf mass per area (LMA), photosynthetic capacity () and have been observed to increase with height, independently of light (Cavender-Bares & Bazzaz, 2000; Thomas & Winner, 2002; Houter & Pons, 2012). Therefore, ontogeny is bound to play a role in thermal sensitivity (Niinemets, 2010; Carter *et al.*, 2021).

**Table 1.** Studies listed here were compiled using a systematic review process, as described in Supplementary Information Methods S3.

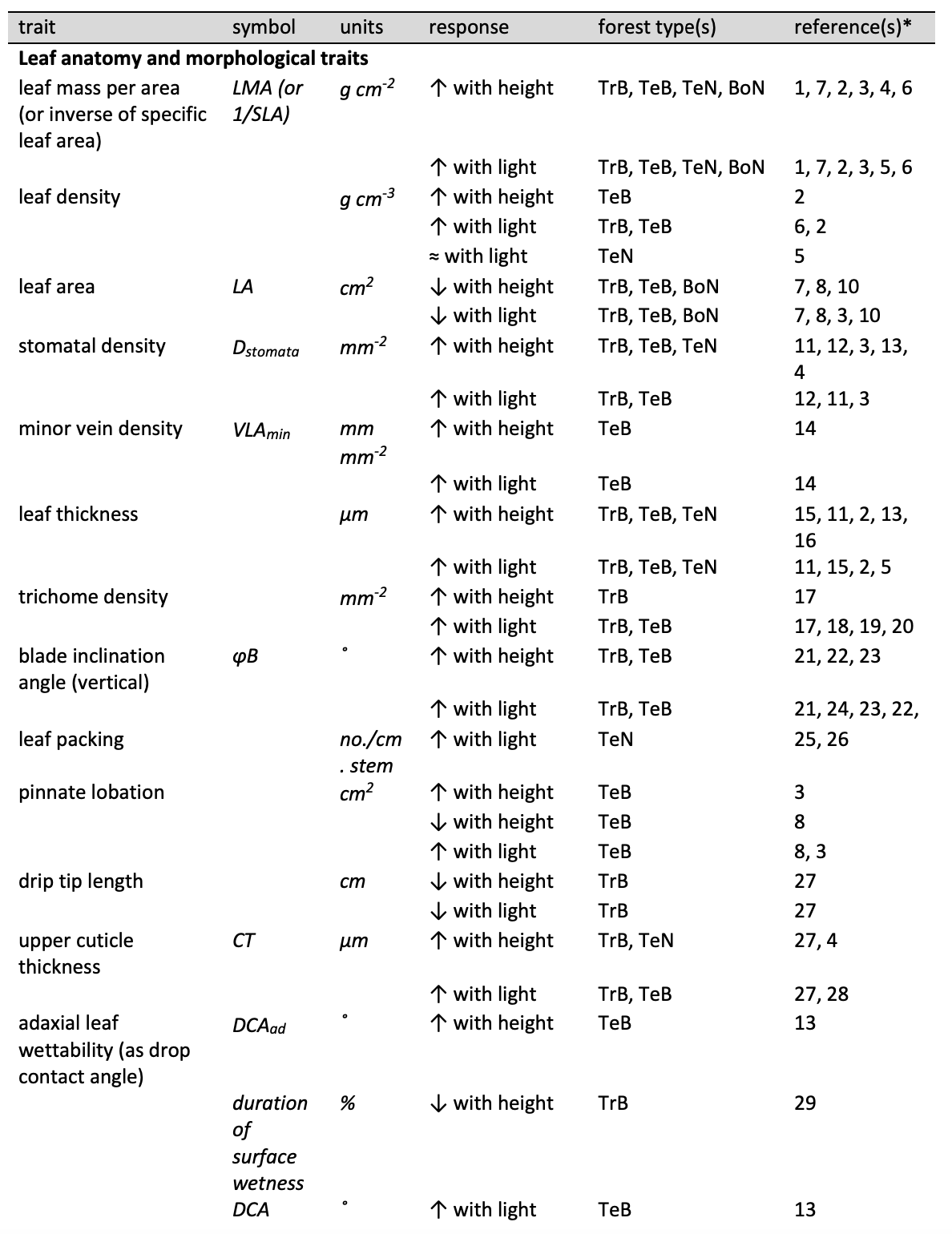
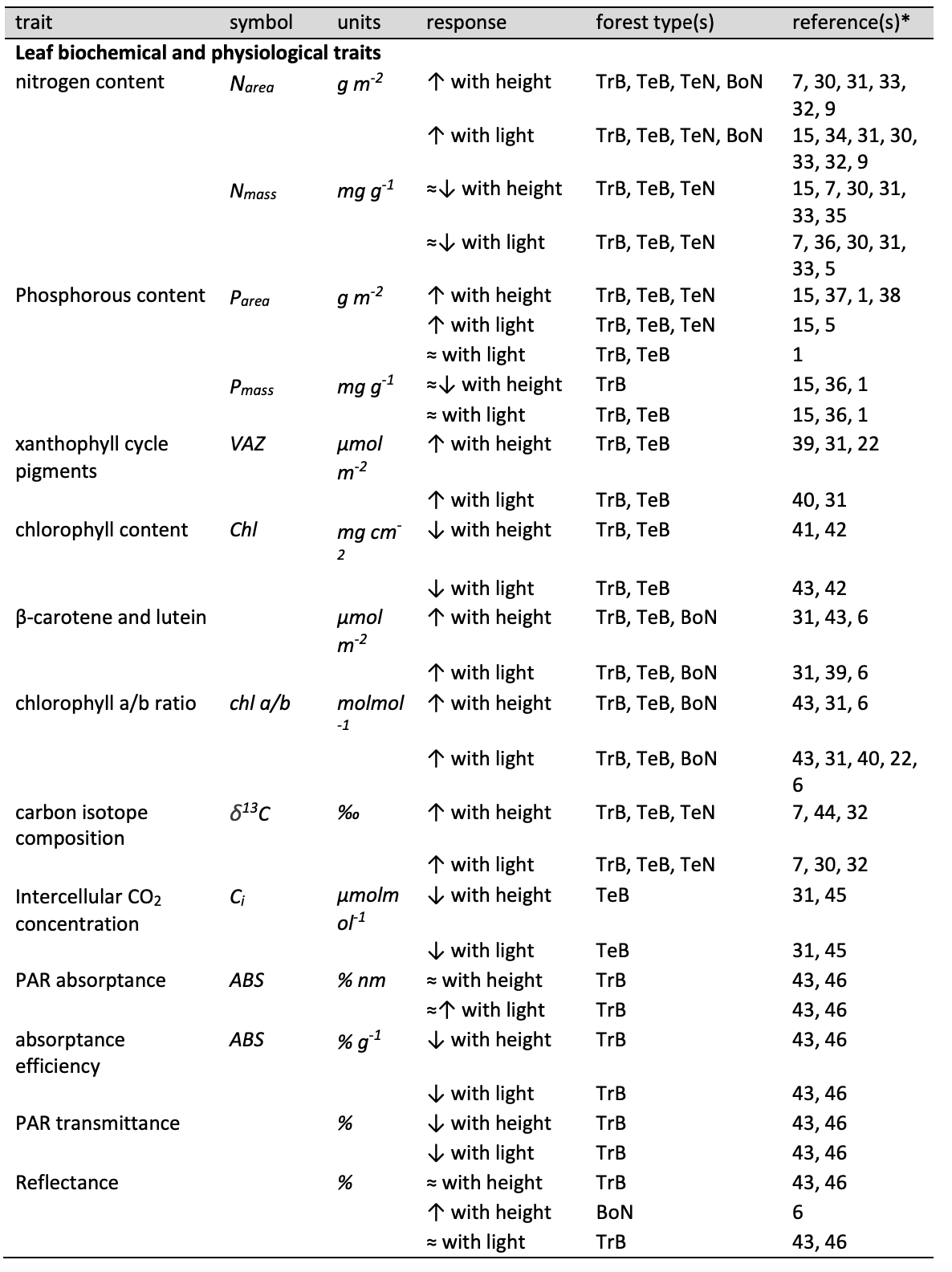


Table 1, cont.



\*1. Mau et al. 2018; 2. Coble and Cavaleri 2014; 3. Sack et al. 2006; 4. Chin and Sillett 2019; 5. Wyka et al. 2012; 6. Atherton et al. 2017; 7. Kenzo et al. 2015; 8. Kusi and Karasi 2020; 9. Dang et al. 1997; 10. Gebauer et al. 2015; 11. Marenco et al. 2017; 12.Kafuti et al. 2020; 13. Van Wittenberghe et al. 2012; 14. Zhang et al. 2019; 15. Weerasinghe et al. 2014; 16. Oldham et al. 2010; 17. Ichie et al. 2016; 18. Gregoriou et al. 2007; 19. Levizou et al. 2005; 20. Liakoura 1997; 21. Fauset et al. 2018; 22. Niinemets et al. 1998, 23. Ishida et al. 1998; 24. Millen and Clendon 1979; 25. Smith and Carter, 1988; 26. Hadley and Smith 1987; 27. Panditharathna et al. 2008; 28. Baltzer and Thomas 2005; 29. Dietz et al. 2007; 30. Coble et al. 2016; 31. Scartazza et al. 2016; 32. Duursma and Marshall, 2006; 33. Harley et al. 1996; 34. Hernandez et al. 2020; 35. Turnbull et al. 2003; 36. Chen et al. 2020; 37. van de Weg et al. 2012; 38. M.A Cavaleri et al. 2008; 39. Koniger et al. 1995; 40. Mastubara et al. 2009; 41. Harris and Medina 2013; 42. Hansen et al. 2001; 43. Poorter et al. 1995; 44. Coble et al. 2017; 45. Niinemets et al. 2004; 46. Poorter et al. 2000

#### (Anatomical, Morphological and Physiological traits)

Sun leaves have traits that reduce heat and water stress – for instance, by being smaller, more pubescent, having higher vein density (Vogel, 1968; Zwieniecki *et al.*, 2004; Sack *et al.*, 2006; Table 1, Leigh *et al.*, 2017; Mathur *et al.*, 2018), and a steeper leaf-angle (Ball *et al.*, 1988; Niinemets, 1998). These traits collectively aid heat dissipation and regulate -photosynthetic balance. In contrast, shade leaves have traits that maximize light capture in the diffuse-light environment with sunflecks (e.g., lower LMA), but they are more likely to overheat than sun leaves due to greater thermal capacitance (Casas *et al.*, 2011; Schymanski *et al.*, 2013; Leigh *et al.*, 2017). In open canopies, where light is comparatively homogeneous, exposed leaves are shaped more by and VPD stress than by light (Mediavilla *et al.*, 2019).

#### (Biochemical and elemental traits, and isoprene)

Elemental concentrations such as and , contribute to high rates of leaf metabolism, including respiration (Meir *et al.*, 2001; Weerasinghe *et al.*, 2014) and photosynthetic processes in sun leaves (Niinemets *et al.*, 2004a; Weerasinghe *et al.*, 2014; Table 1, Scartazza *et al.*, 2016), and may be optimized throughout the vertical canopy gradient (Buckley, 2021). Within-canopy leaf nitrogen distribution can be regulated to prevent photoinhibition in shade leaves during sunflecks, and direct light for sun leaves (Kitao *et al.*, 2018). However, Zhu *et al.* (2018) and O’Sullivan *et al.* (2017) observed no relation between total foliar concentrations of N and P and foliar thermal tolerance.

Biochemical protection against foliage light and heat damage also increases with irradiance, and thus tends to be higher in the upper canopy than in the understory (Table 1). Carotenoids and xanthophyll cycle pigments – violaxanthin, antheraxanthin and zeaxanthin (VAZ) – can play a role in antioxidant scavenging and converting excess excitation energy into heat to reduce photoinhibition (Niinemets *et al.*, 1998; Niinemets, 2007a; Mathur *et al.*, 2018). The dissipation of excess light energy is also important for leaf acclimation to higher temperatures if high impairs the photochemical energy dissipation pathway (Havaux & Tardy, 1996). Heat-sensitive emissions of isoprene gas from tree leaves enhance photosynthetic thermal tolerance by regulating antioxidant defences and other metabolic processes (Sharkey *et al.*, 2008; Taylor *et al.*, 2019; Monson *et al.*, 2021).

#### (Leaf lifecycles)

The vertical structure of microenvironments likely influences forest photosynthetic capacity (Rey-Sánchez *et al.*, 2016) via leaf phenology. For example, deciduousness is an adaptation to conserve water during cold or dry periods (Meakem *et al.*, 2018), but is also structured across the vertical profile. Within tropical deciduous species, the fraction of seasonally deciduous individuals increases toward larger tree size classes in hotter, brighter environments, with understory individuals typically remaining evergreen (Condit *et al.*, 2000). Even in evergreen forests, environmental variation alters leaf age distributions (Albert *et al.*, 2019), which affects forest photosynthetic capacity (Wu *et al.*, 2016; Niinemets, 2016) and heat stress via age-specific leaf function (Albert *et al.*, 2019). For instance, in tropical evergreen forests, because leaf turnover rates of sun leaves in the upper canopy is faster than in the subcanopy, less damage accumulates (Miller *et al.*, 2021). Leaf age affects vulnerability to heat stress and has a strong effect on metabolism (Kikuzawa & Lechowicz, 2006; Zhou *et al.*, 2015; Marias *et al.*, 2017), and can be expected to similarly scale through vertically structured phenology to affect forest responses to heat anomalies.

### Interspecific variation

Vertical gradients in the biophysical environment shape which plant strategies, or sets of traits, are competitive in canopy versus understory conditions, thereby shaping community composition across size classes. Generally, the pattern of fundamental trait adaptations to light gradients across forest species is similar to within-canopy traits (Thomas & Winner, 2002; Rozendaal *et al.*, 2006; Houter & Pons, 2012). For instance, across increasing tree size classes, there is an increase in the fractions of species that are deciduous (Condit *et al.*, 2000; Meakem *et al.*, 2018). However, exceptions exist: at least among evergreen species, shade tolerant species tend to have higher LMA than light demanding species, by contrast with the generally higher LMA for sun than shade leaves within canopies (Lusk *et al.*, 2008). Further, the range in trait values can be several times greater in multi-species canopy than in understory species, based on their inherent species-specific traits and responses to environmental conditions. Therefore, vertical gradients in and metabolism within forest ecosystems are underpinned by both intra- and inter-specific variation in traits.

## Leaf metabolism and thermal responses

Leaf metabolism is strongly shaped by , and by the traits and environmental drivers reviewed above, all of which vary across vertical forest gradients (Fig. 1). However, as we detail below, few studies have evaluated temperature responses of leaf metabolic rates along a vertical canopy gradient, or compared sun and shade leaves (Table 2).

**Table 2.** Summary of observed variation in leaf metabolism and thermal responses across the vertical gradient and/or between sun and shade leaves. Studies listed here were compiled using a systematic review process, as described in Supplementary Information Methods S3.

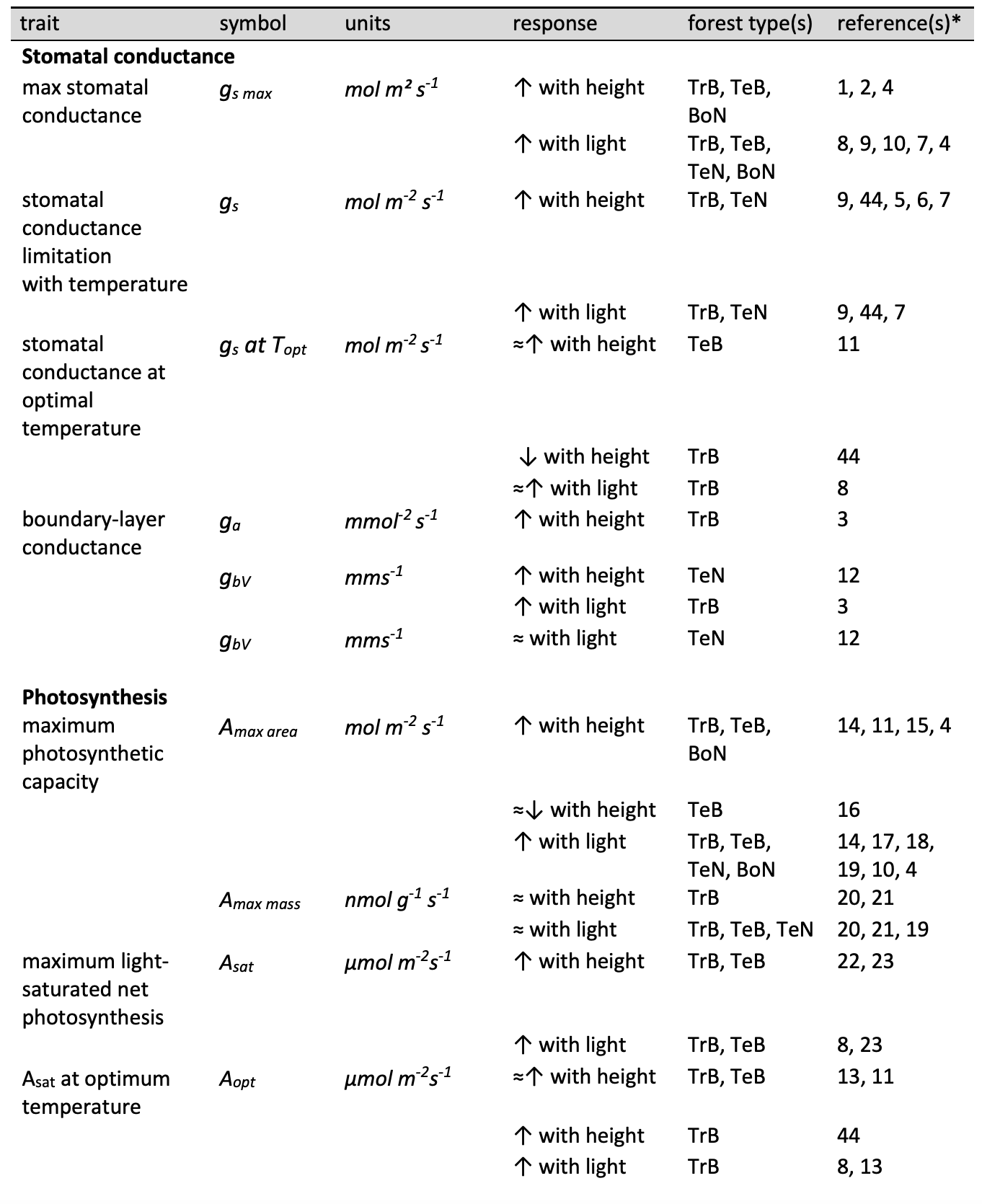


Table 2, cont.

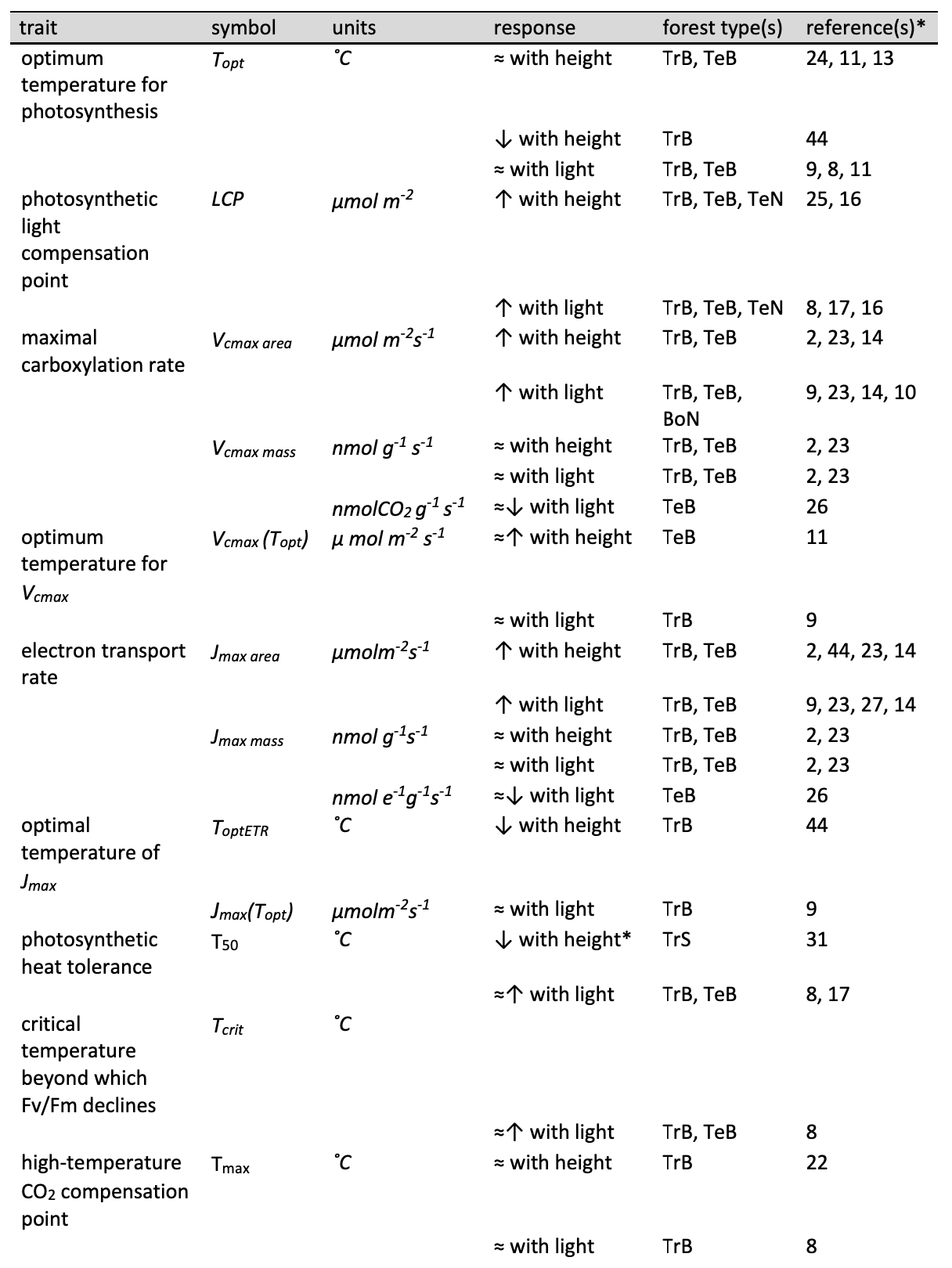
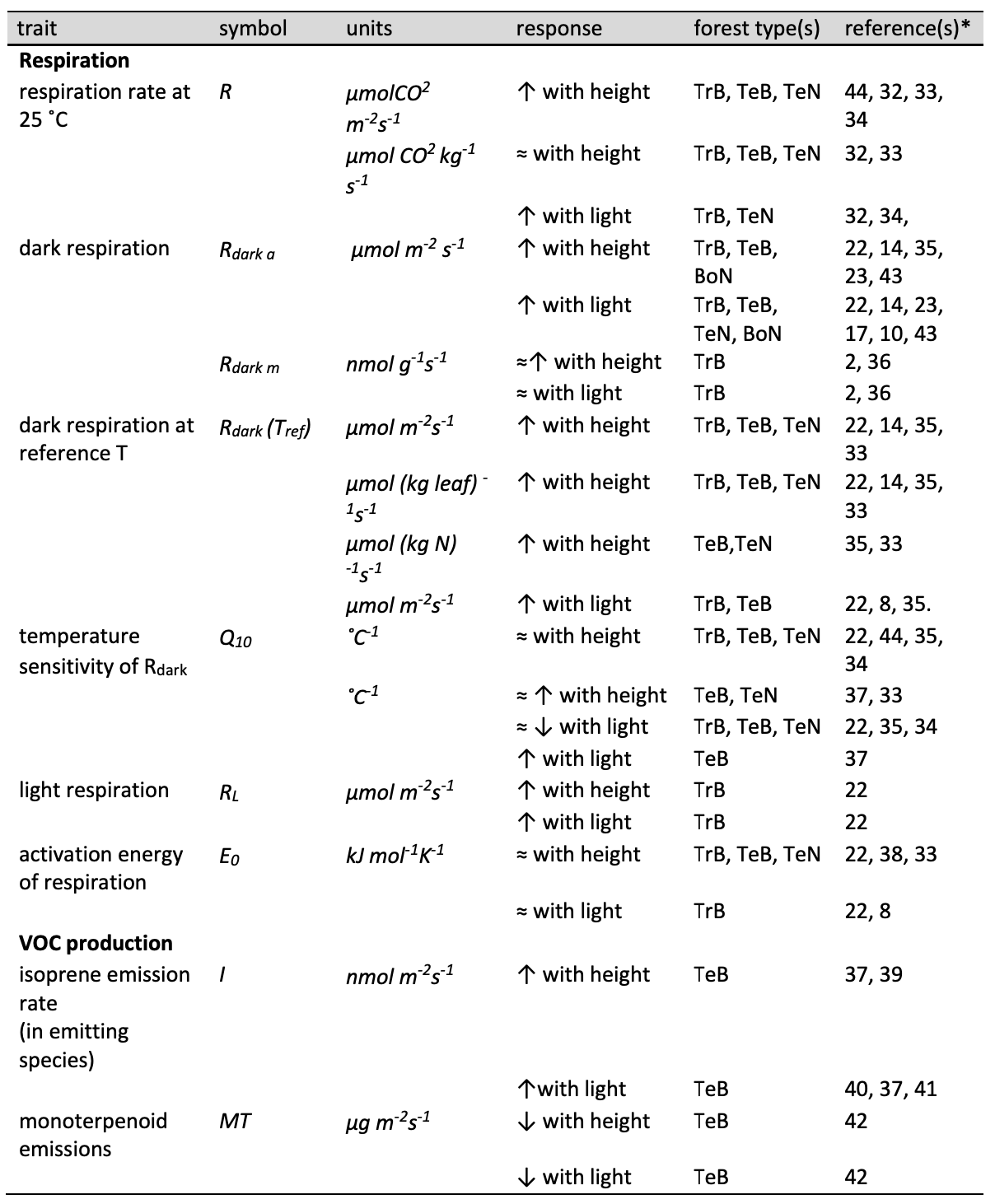


Table 2, cont.



\*1. Kafuti et al. 2020; 2. Van Wittenberghe et al. 2012; 3. Roberts et al. 1990; 4. Dang et al. 1997; 5. Marenco et al. 2017; 6. Ambrose et al. 2015; 7. Zweifel et al. 2001; 8. Slot et al. 2019; 9. Hernandez et al. 2020; 10. Urban et al. 2007; 11. Carter and Cavaleri 2018; 12. Martin et al. 1999; 13. Mau et al. 2018; 14. Kosugi et al. 2012; 15. Niinemets et al. 2015; 16. Bachofen et al. 2020; 17. Hamerlynck and Knapp 1994; 18. Coble et al. 2017; 19. Wyka et al. 2012; 20. Rijkerse et al. 2000; 21. Ishida et al. 1999; 22. Weerasinghe et al. 2014; 23. Scartazza et al. 2016; 24. Miller et al. 2021; 25. Harris and Medina 2013; 26. Legner et al. 2014; 27. Kitao et al. 2012; 28. Fauset et al. 2018; 29. Rey-Sanchez et al. 2016; 30. Muller et al. 2021; 31. Curtis et al. 2019; 32. Mier et al. 2001; 33. Turnbull et al. 2003; 34. Araki et al. 2017; 35. Bolstad et al. 1999; 36. Kenzo et al. 2015; 37. Harley et al. 1996; 38. Xu and Griffin 2006; 39. Harley et al. 1997; 40. Niinemets and Sun, 2014; 41. Sharkey and Monson, 2014; 42. Saimpraga et al. 2013; 43. Atherton et al. 2017; 44. Carter et al. 2021

### Stomatal conductance

Maximum increases with light, and is thus higher in the sun-exposed upper canopy than in sub-canopy or understory leaves (Table 2). However, because of the high VPD and irradiance experienced by sun leaves, midday stomatal depression is more prevalent in sun leaves than shade leaves in closed-canopy forests. In sun leaves, thus further increases due to the lack of transpirational cooling (Koch *et al.*, 1994; Zwieniecki *et al.*, 2004; Kosugi & Matsuo, 2006; Sanches *et al.*, 2010). The temperature at which is maximized, of , did not differ significantly between sun and shade leaves in three tropical tree species (Slot *et al.*, 2019), but sun leaves in the upper canopy show a stronger decrease in in response to rising than do shade leaves in the lower canopy (Hernández *et al.*, 2020; Carter *et al.*, 2021).

### Photosynthesis

**Photosynthetic capacity is generally higher in exposed canopy positions– a fact that is both theoretically expected and observed in numerous field studies [Table 2; Niinemets (2007b) ; Kenzo *et al.* (2015) ; Slot *et al.* (2019); Chen *et al.* (2020)].** This is primarily driven by the greater light available to sun leaves, which also have traits enabling higher photosynthetic rates under high light and sufficient nutrient and water conditions (Table 1, Table 2).

Temperature can affect photosynthesis via direct and indirect pathways: directly, by altering photosynthetic enzyme activity and the electron transport chain, and indirectly through increased VPD causing stomatal closure (Lloyd & Farquhar, 2008). Photosynthesis has a peaked response to , with the peak commonly corresponding to the prevalent ambient growing season conditions (Doughty & Goulden, 2008; Slot & Winter, 2017; Tan *et al.*, 2017). Beyond the optimum, photosynthesis decreases as a result of stomatal closure (Fredeen & Sage, 1999; e.g. Slot & Winter, 2017; Grossiord *et al.*, 2020; Smith *et al.*, 2020), and eventually due to biochemical constraints (Sharkey, 2005; Sage & Kubien, 2007; Vårhammar *et al.*, 2015; Kumarathunge *et al.*, 2019a).

**We have very little evidence as to how the temperature sensitivity of photosynthesis compares between sun and shade leaves.** Based on consistent positive relationships between growth temperature and optimum temperature of photosynthesis () across sites and seasons (e.g. Tan *et al.*, 2017; Kumarathunge *et al.*, 2019a), one might expect sun leaves to have a stronger temperature-dependence and higher temperature optima than shade leaves [Campbell and Norman 1998; Niinemets *et al.* (1999); Niinemets & Valladares (2004)]. However, such a trend is not apparent among recent studies, where for three species in Panama, the for sun leaves tended to be moderately, but not significantly, higher than that of shade leaves (Slot *et al.*, 2019; Hernández *et al.*, 2020). Similarly, of RuBP carboxylation () and regeneration rates () did not differ systematically between tropical sun and shade leaves (Hernández *et al.*, 2020), and along vertical gradients of tropical and temperate trees (Mau *et al.*, 2018; Miller *et al.*, 2021). In contrast, tropical experimental warming observations showed that , and of decrease from the understory to the canopy, potentially linked to greater thermal sensitivity of in upper canopy leaves (Carter *et al.*, 2021).

Hernández *et al.* (2020) also speculated that the observed lack of sun-shade differences in may reflect acclimation to similar temperatures of peak photosynthesis. Sun leaves experience higher temperatures, but maximum temperatures are associated with conditions of midday stomatal depression, and acclimation to optimize photosynthesis at these temperatures would not be advantageous. Shade leaves that do not experience midday depression continue to fix carbon even when afternoon air temperatures peak (Miller *et al.*, 2021). Evaluating this requires diurnal monitoring of net photosynthesis through the canopy.

**Leaf photosynthetic thermal tolerance** Irreversible damage to photosystem II, leading to leaf necrosis and eventually leaf death, occurs at of (Baker, 2008; Feeley *et al.*, 2020). Thermal tolerance is described in terms of the temperature at which efficiency of photosystem II starts to decrease, , and the at which efficiency of photosystem II had decreased by 50%, (Slot *et al.*, 2021a). Thermal tolerance varies globally across latitude and climate, where and decrease across latitudes, and with elevation among tropical forests (O’Sullivan *et al.*, 2017; Feeley *et al.*, 2020; Slot *et al.*, 2021a).

Leaf thermal tolerances are more closely adapted to microclimate than macroclimate (Feeley *et al.*, 2020; Slot *et al.*, 2021a). Chinquapin oak (*Quercus muehlenbergii*) growing in xeric, sunnier conditions showed higher by than bur oak (*Quercus macrocarpa*) growing in shaded mesic conditions (Hamerlynck & Knapp, 1996). In Australia, along a vertical gradient within the canopy, *Acacia papyrocarpa* (Benth.) showed greater and higher composite climate stress in the lower, north-facing canopy than other canopy positions, correlating with low wind-speed, greater radiation and , and lower rates of heat dissapation, as indicated by longer leaf thermal time constants (Curtis *et al.*, 2019). Additionally, thermal tolerances are explained more by leaf traits than phylogeny (Feeley *et al.*, 2020; Slot *et al.*, 2021a). was found to be greater among tropical species with large leaves that had slow heating and cooling time, whereas was greater among species with greater LMA (Slot *et al.*, 2021a). Across species sun leaves that experienced higher maximum temperatures show higher photosynthetic heat tolerance (Perez & Feeley, 2020). However, considering sun and shade leaf differences within canopy (Table 1), varies modestly, being slightly lower for shade than sun leaves for two of three tree species in Panama (Slot *et al.*, 2019). The small difference in coupled with large differences in across thermal microenvironments implies that more thermally tolerant leaves tend to operate closer to their thermal limits and could therefore be more vulnerable to heat anomalies (Perez & Feeley, 2020).

### Respiration

**Similar to photosynthesis, respiration tends to be higher in canopy sun-leaves (Table 2, Chen *et al.*, 2020), but its temperature sensitivity () shows no definite trend along the vertical gradient (Bolstad *et al.*, 1999; Weerasinghe *et al.*, 2014).** Specifically, the of respiration can be constant within vertical profiles and in seedling sun vs. shade leaves (Bolstad *et al.*, 1999; Xu & Griffin, 2006; Zaragoza-Castells *et al.*, 2007, 2008; Weerasinghe *et al.*, 2014; Carter *et al.*, 2021), greater in upper-canopy leaves (Harley *et al.*, 1996; Turnbull *et al.*, 2003), or greater in the lower canopy (Griffin *et al.*, 2002). This may vary based on forest type [**REF**], acclimation to high temperature that decreases (Slot & Kitajima, 2015), or leaf traits and leaf age, as in evergreen species, has shown to be greater in younger than older leaves (Zhou *et al.*, 2015). Recent observations suggest that tropical understory leaves down-regulate with rising (Carter *et al.*, 2021).

### VOC production

**The vertical structuring of leaf isoprene emissions may indicate the importance of temporal variability in thermal conditions as distinct from the long-term average.** Isoprene gas emission from tree leaves is associated with photosynthetic thermal tolerance (Sharkey *et al.*, 2008; Taylor *et al.*, 2019), and within species, emission rates tend to increase toward brighter and hotter microenvironments (Niinemets *et al.*, 2010). Across landscapes, emitting species increase in relative abundance toward hotter climates, exceeding half of trees in warm tropical forests (Taylor *et al.*, 2018). In contrast, a recent inventory in an Amazon forest showed that both the abundance of emitting species and average emission rates were highest in the mid-canopy region instead of the hotter and brighter upper canopy (Taylor *et al.*, 2021). This observation is consistent with the hypothesis that temperature sensitive isoprene emissions enable real-time acclimation to rapidly changing leaf thermal environments typical of the mid-canopy region (Sharkey *et al.*, 2008), due to the sun’s passage across a dynamically structured canopy surface. This review focuses primarily on variation in mean conditions across the vertical profile, but future work should seek to understand how temporal dynamics of leaf heating (see Leigh *et al.*, 2017) vary through the canopy and influence leaf function.

## Whole-tree and ecosystem ecology

**Differences across forest vertical gradients in biophysical conditions, plant traits, and metabolism scale up to affect whole-tree ecology, ecosystem ecology, and their temperature responses (Fig. 1).**

### Tree metabolism and growth, and survival

**Vertical gradients affect tree metabolism and growth.** Whole-tree transpiration and gross primary production (GPP) increase in tandem with increasing tree size, where size is most commonly measured as diameter at breast height (DBH), but functionally linked to metrics such as foliage biomass, crown volume, and height, all of which scale with DBH (Meinzer *et al.*, 2001; Anderson-Teixeira *et al.*, 2015; Kunert *et al.*, 2017). Specifically, increases are linked to increased leaf area and in part to an increasing probability that the crown is in the canopy (Muller-Landau *et al.*, 2006), where higher light availability and associated elevation of and result in higher leaf area-specific transpiration and photosynthesis (Table 2). The net foliar photosynthate production is allocated among functions including respiration, woody growth, foliar turnover, root growth and allocation to root-associated microorganisms, reproduction, defense, and storage of non-structural carbohydrates (NSCs). Within a stand, woody growth rates , measured as radial stem growth or biomass increment, generally increase with tree size (e.g., Muller-Landau *et al.*, 2006, Stephenson et al. 2014). NSC reserves also increase with tree size, such that larger trees have relatively more buffer against biological and biophysical stressors (Niinemets, 2010).

**Vertical gradients also affect the climate sensitivity of metabolism and growth.** Stomatal conductance tends to be more strongly limited by high atmospheric demand (high and VPD, low RH) even before soil water becomes limited in forests not experiencing drought (Corlett, 2011; Ruehr *et al.*, 2016; Novick *et al.*, 2016). Therefore, periods of high atmospheric demand–be these on time scales of hours, days, or seasons–tend to cause greater reductions in whole-tree transpiration and photosynthesis in tall trees that occupy canopy positions in relatively dense-canopy forests (Christoffersen *et al.*, 2016; Garcia *et al.*, 2021). This is consistent with the observation that -limitation with increases with height in the canopy (Table 2). More active stomatal regulation of tall canopy trees (e.g., Mediavilla & Escudero, 2004)– often combined with greater effective rooting depth–may offset greater xylem embolism risk (Olson *et al.*, 2018; Garcia *et al.*, 2021; **chitra-tarakHydraulicallyvulnerableTreesSurvive2021?**) and lower capacity to adjust traits related to carbon metabolism to drought (Bartholomew *et al.*, 2020). This results in decreasing carbon isotope discrimination, indicative of an increasingly conservative hydraulic strategy, with increasing tree height (Table 1, McDowell *et al.*, 2011).

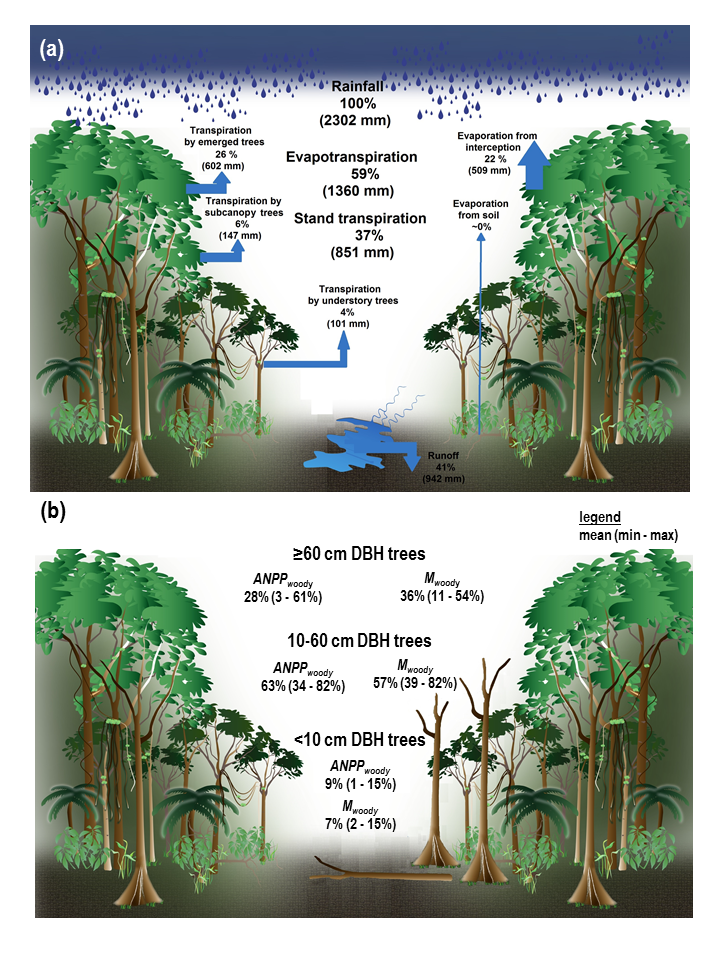
In turn, the climate sensitivity of woody growth tends to be greater in canopy trees. In the field of dendrochronology, it is generally accepted that tree ring records of large, exposed trees are best suited for climate reconstructions because their annual growth displays the greatest sensitivity to interannual variation in climate (Fritts, 1976). However, only a relatively limited number of studies have directly examined drought- or temperature-sensitivities as a function of tree size. These have generally found greater sensitivity to low precipitation or seasonally high temperatures among larger, more exposed trees (**Fig. 4**, Trouillier *et al.*, 2018; Gillerot *et al.*, 2020; McGregor *et al.*, 2021), corroborating evidence from globally disurbed forest censuses that larger trees tend to undergo larger growth declines during drought (Bennett *et al.*, 2015). In addition to lower drought resistance of growth, larger trees frequently exhibit lower ability to recover from stress (Gillerot *et al.*, 2020; ie. resilience, McGregor *et al.*, 2021), and greater increases in mortality (Bennett *et al.*, 2015; Stovall *et al.*, 2019). Despite the potential for shorter trees in open forests to experience greater environmental stress (Curtis *et al.*, 2019), this pattern has been observed in open as well as closed-canopy forests (Bennett *et al.*, 2015; Anderson-Teixeira *et al.*, 2021). However, exceptions to the pattern of greater growth reductions under high among larger trees. In eight mesic forests across the northeast United States, tree-ring records showed steep growth declines of understory trees at higher , contrasting with the responses of canopy trees (Fig 4, Rollinson *et al.*, 2020). Additional research is required to understand the mechanisms underlying these intriguing differences, and to disentangle size-related tree growth responses to hot-wet versus hot-dry conditions.



**Figure 4. Examples of tree-ring analyses showing differential interannual temperature sensitivity of annual growth between large canopy versus smaller understory trees.** In column (a), across three sites and species, trees with large diameter breast height (DBH) had more negative growth responses to high temperatures during the current or previous growing season (denoted by c or p, respectively, on the x axes) than did small trees of the same species. Shown are tree ring width responses to the most influential temperature variable at the site ( or PET) for the maximum and minimum tails of the DBH distribution included in the analysis. Colored lines represent responses to the temperature variable in a model including a DBH - temperature interaction. Other model terms are held constant at their mean. Transparent ribbons indicate 95% confidence intervals. Vertical grey lines and shading indicate the long-term mean 1 standard deviation of the temperature variable. From Anderson-Teixeira et al. (in revision). In column (b), understory trees of four species had more negative growth responses to high growing season temperatures across eight New England forests. Growth is expressed as relativized basal area increment (BAI), where values > and < 100% indicate higher- or lower- than-average growth, respectively. Again, colored lines indicate modeled mean temperature responses and transparent ribbons indicate 95% confidence intervals. From Rollinson *et al.* (2020).

### C and water flux

**Canopy trees account for the majority of forest ecosystem water and carbon cycling.** While studies partitioning transpiration across forest vertical gradients are rare, both ET and transpiration have been shown to increase with height in a *Picea abies* forest in Germany, such that the upper half of the canopy contributed an estimated 80% of daytime ET (Staudt *et al.*, 2011). Similarly, in a tropical forest in the Brazilian Amazon, canopy and subcanopy trees jointly contributed approximately 93% of ET, or 88% of transpiration [Fig 5a; Kunert *et al.* (2017)], and trees >33 cm DBH contributed >80% of transpiration in a forest in Costa Rica (Moore *et al.*, 2018). In terms of C cycling, it has been estimated that canopy strata contribute 64% of net daytime CO2~ uptake [i.e., GPP - ecosystem respiration, including from soil; Misson *et al.* (2007)]. Large trees also dominate in terms of woody aboveground net primary productivity () and mortality (), with trees 10cm DBH usually contributing > 85% of ANPPwoody and Mwoody across 25 globally distributed forests (Fig. 5b, **piponiot\_sizerelated\_inreview?**).



**Figure 5.** Vertical partitioning of (a) evapotranspiration and (b) C fluxes in tropical forests. Panel (a) is from Kunert *et al.* (2017); panel (b) presents averages for 42 tropical forests from (**piponiot\_sizerelated\_inreview?**).

**It is less clear how thermal sensitivity of water and carbon fluxes vary across strata, but likely responses can be inferred based on the patterns and mechanisms reviewed above.** We expect that transpiration, GPP, and should all be sensitive to high temperatures– at least under conditions of moderate to high VPD (Grossiord *et al.*, 2020). Further, increases in canopy are also shown to reduce forest GPP in the tropics (Pau *et al.*, 2018). A rare example of a study comparing the climate sensitivity of C fluxes across size classes (Meakem *et al.*, 2018) showed that was more strongly elevated among large than small trees during an El Nino drought in Panama, while the smallest size classes had higher productivity during the drought, likely because of increased light in the understory. It remains far less clear how thermal sensitivity varies across forest strata under wet conditions, but both physiological mechanisms (Fig. 3) and tree ring evidence (Fig. 4) suggests that understory trees may respond more negatively to hot, wet conditions. Further research is required to better understand the thermal sensitivity of forest ecosystem function across strata.

## Implications

Having established how physical conditions and biological form and function vary across vertical gradients, we now turn attention to the implications of these patterns for our understanding of how forest ecosystems may be impacted by global change, and our ability to project this across space and time.

## Global change responses

The complex interwoven relations between the biophysical environment and biological factors–leaf traits, metabolic processes and distribution of trees– are likely to produce amplifications and feedback loops in a warming world, with implications for forests on many levels.

### Warming

Warming impacts forests, from leaf metabolism to whole forest structure. Leaf level is closely related ecosystem . Temperature limitations to leaf processes, such as VPD and gs-limitation, can modify ecosystem if species do not acclimate, resulting in reduced carbon sequestration (Tan *et al.*, 2017; Huang *et al.*, 2019; Way, 2019; Bennett *et al.*, 2021a). At a metabolism level, leaf photosynthesis and respiration are coupled to photosynthetic thermal optima. Beyond this inflection point, photosynthesis declines whereas respiration continues to increase exponentially, eventually shifting the carbon balance from sink to source, independent of water and irradiance (Duffy *et al.*, 2021). Exposed canopies are likely most vulnerable, as current growing season temperatures are equal to, or higher than photosynthetic optima of temperature and tropical forests (Slot & Winter, 2017; Mau *et al.*, 2018; Kumarathunge *et al.*, 2019b; Huang *et al.*, 2019), and leaf temperatures may approach lethal temperatures (e.g., O’Sullivan *et al.*, 2017; Tiwari *et al.*, 2021). A buffering effect from the canopies might allow shaded layers to photosynthesize longer in the day (He *et al.*, 2018; Miller *et al.*, 2021), especially if RH in the understory does not inhibit transpirational cooling. Thermal limits are especially narrow in tropical and mid-latitudes forests (O’Sullivan *et al.*, 2017). A daytime temperature threshold of 32 degrees C has been suggested for long term climate sensitivity of global tropical forests, where reduced growth, and increased drought and tree mortality will lead to increased carbon source than sink (Sullivan *et al.*, 2020). In the understory, warming is disproportionately affecting the less thermally-adapted plant species, resulting in associated plant community thermophilization (Duque *et al.*, 2015; Greiser *et al.*, 2019; Zellweger *et al.*, 2020). Canopy disturbance (see next section) along with a trend towards younger forests and again reduced tree growth associated with warming (McDowell *et al.*, 2020) poses an increasing threat to the biodiversity of microrefugia that are otherwise buffered from extremes (Scheffers *et al.*, 2013; Greiser *et al.*, 2019).

### Canopy disturbance

Canopies are crucial to microclimatic stratification, as they buffer several aspects of forest microenvironments (Figs 1-2, Zellweger *et al.*, 2019), particularly in wetter environments with dense canopies (Davis *et al.*, 2019a). Severe droughts and rising temperatures place canopies at risk, as larger trees tend to suffer more during droughts (Bennett *et al.*, 2015). The disproportionate impact of disturbance on large trees holds for other types of disturbance, including forest fragmentation and logging [(Laurance *et al.*, 2006; Miller *et al.*, 2011), although fire tends to predominantly affect smaller trees (Brando, 2019). Canopy structure affects understory species composition, which has been shown to shift under warming and canopy disturbance (Maes *et al.*, 2020; Majasalmi & Rautiainen, 2020; Bertrand *et al.*, 2020)

In general, disturbances (e.g., drought, fire, fragmentation, and logging) reduce canopy cover, which in turn increases incident radiation levels and temperatures within the canopy (Stark *et al.*, 2020). This shift to hotter and drier microclimates often makes forests more susceptible to further disturbances, for example, increasing fire risk (Brando *et al.*, 2014; Aragão *et al.*, 2018). Severe degradation impacts can cause dramatic ecological state changes (e.g., the transition from forest to more open, savanna-like vegetation in tropical forest regions through ‘savannization’) and non-linear threshold responses in energy balance and associated microclimates, with implications for forest-atmosphere interactions (Stark *et al.*, 2020).

Variation in resistance and resilience among forests may drive different trajectories in the face of global climate change. For example, African rainforests, with canopy trees that are more resilient to warming and drought than other forests (Bennett *et al.*, 2021b). Species with smaller leaves and larger gs will be less vulnerable to temperature increase than species with larger leaves (Fauset *et al.*, 2018; Song *et al.*, 2020) and isoprene emitting species will have a selective advantage in a warming world (Taylor *et al.*, 2019). Temperature acclimation (Cunningham & Read, 2003; Slot & Kitajima, 2015; Way, 2019; Slot *et al.*, 2021b) and recovery from canopy heat stress (Smith *et al.*, 2020) will also help forests cope with warming.

These shifts in forest structure at large may be detectable by lidar and thermal remote sensing. If we know how metabolism maps to the thermal profile, then the observed forest structural changes can inform prediction of forest function.

## Scaling across space and time

### Representing Vertical Gradients in Models

Models are needed to predict future ecosystem dynamics, which remain one of the largest sources of uncertainty in Earth System Model (ESM) projections of the future of global carbon cycling and climate change (Friedlingstein *et al.*, 2006). Dynamic global vegetation models (DGVMs), which comprise the land surface models in ESMs, are used to predict the global distribution of vegetation types and biosphere-atmosphere feedbacks (Foley *et al.*, 1996; Sitch *et al.*, 2003; Woodward & Lomas, 2004). DGVMs operate at a range of scales and vary in complexity, from detailed individual-based models (i.e., forest gap models), which represent vegetation at the level of individual plants, capturing spatial variability in the light environment and microclimates at high vertical and horizontal spatial resolution (Shugart *et al.*, 2018), to big-leaf models that reduce 3D vegetation structure across the entire biosphere into a single vegetation layer (Bonan *et al.*, 2003; Krinner *et al.*, 2005). This simplification is computationally more efficient, although it comes at a cost of a lack of representation of important demographic processes and vertical light competition (Hurtt *et al.*, 1998; Smith *et al.*, 2001; Krinner *et al.*, 2005). The computational middle-ground to representing vertical structure in DVGMs lies in cohort-based models (CBMs), which sit between the oversimplified vegetation dynamics in big-leaf models and the computational expense of individual-based models. CBMs represent vegetation as cohorts of individual plants, grouped together based on properties including size, age, and functional type (Fisher *et al.*, 2018).

**The findings of this review reinforce the notion that representing vertical structuring is essential to capturing forest dynamics under global change.** Improved representation of vertical variation in forest canopy architecture and ecosystem function is critical for representing thermal sensitivity and has repeatedly been identified as an important step toward reduced uncertainty and more accurate characterization of biologically mediated feedbacks (Moorcroft *et al.*, 2001; Banerjee & Linn, 2018; Bonan *et al.*, 2021). In addition, this review finds that, although larger trees face disproportionate stress during drought, understory trees have fewer cooling mechanisms and may also be stifled under hot, humid conditions. **A key question is whether existing models adequately represent the processes that underpin understory tree responses to thermal stress as well as large tree responses.** Most models have been developed to capture dynamics in the canopy, or overstory, given the disproportionate role of these large trees in ecosystem dynamics. Less attention has focused on developing and validating understory tree dynamics and responses to perturbations in models. This is likely due in large part to the fact that observations are only beginning to shed light on the vulnerability of understory trees to changes in temperature and other abiotic conditions (e.g., Rollinson *et al.*, 2020).

Though an improvement over big-leaf models, DGVMs that separate the canopy into only two layers (e.g., sunlit and shaded portions) may not be able to capture important within-canopy variation in terms of leaf dynamics (e.g., seasonal shifts in vertical leaf area distributions, Smith *et al.*, 2019a) and functions (e.g., thermal responses, as we present in this paper). At the very least, multi-layered ecosystem models will likely be necessary for accurately predicting future forest function (e.g., De Pury & Farquhar, 1997; Bonan *et al.*, 2021). In addition, capturing the vertical gradients in NPP, GPP, and respiration, and subsequently the net ecosystem effects, requires improved characterization of the functional response of leaf-level processes to vertically varying abiotic conditions, and the role of traits and abiotic conditions in mediating responses to thermal sensitivity.



**Figure 6.** Lidar and thermal remote sensing data can be used to measure vertical canopy structure and plant thermal signatures at increasingly large scales. (a-b) Integrating in situ and remote sensing measurements will support our ability to scale understanding of vertical gradients within and across ecosystems. (c) In turn, these efforts can be used to directly inform ecosystem model development and parameterization. Vertically resolved in situ data could include any variable listed in Table 1 or 2.

**Scaling in situ data with remote sensing**

Remote sensing data provide a valuable means to scale between in situ observations and DGVMs. Specifically, the increasing availability of airborne and spaceborne LiDAR and thermal remote sensing data offer a promising opportunity for mapping vertical thermal gradients in combination with vegetation structure at locations with in situ data and across larger landscapes (Fig. 6). Airborne and spaceborne lidar, as well as terrestrial laser scanning data yield detailed 3D reconstructions of whole tree and forest structure. These data can be leveraged in combination with thermal remote sensing data from the spaceborne ECOSTRESS sensor (Hulley *et al.*, 2019; Fisher *et al.*, 2020) or drone- and tower-based FLIR cameras.

Detailed structural information from lidar data has been used to measure tree height, DBH, and crown dimensions (Fisher *et al.*, 2020), evaluate spatial variation in vertical leaf area density profiles (Detto *et al.*, 2015), and resolve complex seasonal and diurnal variation in shortwave radiation forcing in ecosystems (Musselman *et al.*, 2013). In addition, shading by the overstory can be better represented to predict understory temperatures by modeling the time-varying interaction of the forest canopy with solar radiation, as has been done in other LIDAR-based analyses (e.g., Davis *et al.*, 2019b). Satellite and airborne thermal infrared remote sensing analyses are now being conducted at regional and continental scales, although very few applications exist at finer-scales necessary for understanding of vertical variation in plant canopy temperatures (Johnston *et al.*, 2020 in review). (Pau *et al.*, 2018) used data from a tower-based FLIR camera in combination with eddy-covariance data and found that tropical forest canopy temperatures were more strongly associated with GPP than air temperatures or VPD. In a savanna system in the western U.S., (Johnston *et al.*, 2020 in review) found significant vertical variation in plant temperature, with warmer temperatures in the understory compared to the top of the blue oak canopies. This finding was the opposite of what was expected and occurred in association with very high grass temperatures. The growing availability of these data makes this an opportune time to link fine-scale and landscape-scale measurements with the type of in situ measurements reviewed above to further explore ecosystem-scale patterns in vertical temperature gradients seasonally and across biomes.

## Conclusions

* across vertical gradients, directional trends in biophysical environment and leaf traits are the rule, suggesting that the physiology and ecology that have these as their underpinnings should also vary
* a number of studies confirm that this is the case.
* However, when we ask the critical question of how the temperature sensitivities of metabolism and woody growth varies across these different environments, we can’t say much– there are only a small number of studies, often showing insignificant differences or mixed results.
* The preponderance of available data suggest that while large canopy trees are the most vulnerable to warming when water is limited, understory trees may be more vulnerable under more mesic conditions, but more research is needed.
* Critically, change to the vertical gradient–e.g., through increased mortality of canopy trees–will change processses across forest strata, with potentially dramatic consequences. (some of the literature on forest degredation or fragmentation could inform what happens when those gradients change)

## Acknowledgements

Thanks to …., the ForestGEO Ecosystems & Climate lab at SCBI for helpful discussion. Funding was provided by the Smithsonian Institution, ….

## SI files

Methods S1. Methods for analyzing vertical gradients in the biophysical environment

Methods S2. Methods for leaf energy balance modeling

Methods S3. Methods for literature review

Table S1. National Ecological Observatory Network (NEON) sites included in the analysis of vertical gradients of key biophysical characteristics

Table S2. (Tealeaves parameters)

Figure S1. Vertical gradients in micrometeorological conditions for all forested sites in the National Ecological Observatory Network (NEON)

## References

**Albert LP, Restrepo-Coupe N, Smith MN, Wu J, Chavana-Bryant C, Prohaska N, Taylor TC, Martins GA, Ciais P, Mao J, *et al.*** **2019**. Cryptic phenology in plants: Case studies, implications, and recommendations. *Global Change Biology* **25**: 3591–3608.

**Almeida DRA de, Nelson BW, Schietti J, Gorgens EB, Resende AF, Stark SC, Valbuena R**. **2016**. Contrasting fire damage and fire susceptibility between seasonally flooded forest and upland forest in the Central Amazon using portable profiling LiDAR. *Remote Sensing of Environment* **184**: 153–160.

**Ambrose AR, Sillett SC, Koch GW, Van Pelt R, Antoine ME, Dawson TE**. **2010**. Effects of height on treetop transpiration and stomatal conductance in coast redwood (Sequoia sempervirens). *Tree Physiol* **30**: 1260–1272.

**Anderson-Teixeira KJ, Herrmann V, Banbury Morgan R, Bond-Lamberty B, Cook-Patton SC, Ferson AE, Muller-Landau HC, Wang MMH**. **2021**. Carbon cycling in mature and regrowth forests globally. *Environ. Res. Lett.* **16**: 053009.

**Anderson-Teixeira KJ, McGarvey JC, Muller-Landau HC, Park JY, Gonzalez-Akre EB, Herrmann V, Bennett AC, So CV, Bourg NA, Thompson JR, *et al.*** **2015**. Size-related scaling of tree form and function in a mixed-age forest. *Functional Ecology* **29**: 1587–1602.

**Aragão LEOC, Anderson LO, Fonseca MG, Rosan TM, Vedovato LB, Wagner FH, Silva CVJ, Silva Junior CHL, Arai E, Aguiar AP, *et al.*** **2018**. 21st Century drought-related fires counteract the decline of Amazon deforestation carbon emissions. *Nat Commun* **9**: 536.

**Araki MG, Gyokusen K, Kajimoto T**. **2017**. Vertical and seasonal variations in temperature responses of leaf respiration in a Chamaecyparis obtusa canopy. *Tree Physiology* **37**: 1269–1284.

**Ashton PS, Hall P**. **1992**. Comparisons of Structure Among Mixed Dipterocarp Forests of North-Western Borneo. *Journal of Ecology* **80**: 459–481.

**Atherton J, Olascoaga B, Alonso L, Porcar-Castell A**. **2017**. Spatial Variation of Leaf Optical Properties in a Boreal Forest Is Influenced by Species and Light Environment. *Front. Plant Sci.* **8**.

**Aussenac G**. **2000**. Interactions between forest stands and microclimate: Ecophysiological aspects and consequences for silviculture. *Ann. For. Sci.* **57**: 287–301.

**Bachofen C, D’Odorico P, Buchmann N**. **2020**. Light and VPD gradients drive foliar nitrogen partitioning and photosynthesis in the canopy of European beech and silver fir. *Oecologia* **192**: 323–339.

**Baker NR**. **2008**. Chlorophyll Fluorescence: A Probe of Photosynthesis In Vivo. *Annu. Rev. Plant Biol.* **59**: 89–113.

**Baldocchi DD, Vogel CA, Hall B**. **1997**. Seasonal variation of energy and water vapor exchange rates above and below a boreal jack pine forest canopy. *Journal of Geophysical Research: Atmospheres* **102**: 28939–28951.

**Ball MC, Cowan IR, Farquhar GD**. **1988**. Maintenance of Leaf Temperature and the Optimisation of Carbon Gain in Relation to Water Loss in a Tropical Mangrove Forest. *Functional Plant Biol.* **15**: 263–276.

**Baltzer JL, Thomas SC**. **2005**. Leaf optical responses to light and soil nutrient availability in temperate deciduous trees. *American Journal of Botany* **92**: 214–223.

**Banerjee T, De Roo F, Mauder M**. **2017**. Explaining the convector effect in canopy turbulence by means of large-eddy simulation. *Hydrology and Earth System Sciences* **21**: 2987–3000.

**Banerjee T, Linn R**. **2018**. Effect of Vertical Canopy Architecture on Transpiration, Thermoregulation and Carbon Assimilation. *Forests* **9**: 198.

**Barnard DM, Bauerle WL**. **2016**. Seasonal Variation in Canopy Aerodynamics and the Sensitivity of Transpiration Estimates to Wind Velocity in Broadleaved Deciduous Species. *Journal of Hydrometeorology* **17**: 3029–3043.

**Bartemucci P, Messier C, Canham CD**. **2006**. Overstory influences on light attenuation patterns and understory plant community diversity and composition in southern boreal forests of Quebec. *Can. J. For. Res.* **36**: 2065–2079.

**Bartholomew DC, Bittencourt PRL, Costa ACL da, Banin LF, Costa P de B, Coughlin SI, Domingues TF, Ferreira LV, Giles A, Mencuccini M, *et al.*** **2020**. Small tropical forest trees have a greater capacity to adjust carbon metabolism to long-term drought than large canopy trees. *Plant, Cell & Environment* **43**: 2380–2393.

**Bennett AC, Arndt SK, Bennett LT, Knauer J, Beringer J, Griebel A, Hinko-Najera N, Liddell MJ, Metzen D, Pendall E, *et al.*** **2021a**. Thermal optima of gross primary productivity are closely aligned with mean air temperatures across Australian wooded ecosystems. *Global Change Biology* **n/a**.

**Bennett AC, Dargie GC, Cuni-Sanchez A, Mukendi JT, Hubau W, Mukinzi JM, Phillips OL, Malhi Y, Sullivan MJP, Cooper DLM, *et al.*** **2021b**. Resistance of African tropical forests to an extreme climate anomaly. *PNAS* **118**.

**Bennett AC, McDowell NG, Allen CD, Anderson-Teixeira KJ**. **2015**. Larger trees suffer most during drought in forests worldwide. *Nature Plants* **1**: 15139.

**Bertrand R, Aubret F, Grenouillet G, Ribéron A, Blanchet S**. **2020**. Comment on ‘Forest microclimate dynamics drive plant responses to warming’. *Science* **370**.

**Bolstad PV, Mitchell K, Vose JM**. **1999**. Foliar temperature–respiration response functions for broad-leaved tree species in the southern Appalachians. *Tree Physiology* **19**: 871–878.

**Bonan GB**. **2016**. *Ecological climatology: Concepts and applications*. New York, NY, USA: Cambridge University Press.

**Bonan GB, Levis S, Sitch S, Vertenstein M, Oleson KW**. **2003**. A dynamic global vegetation model for use with climate models: Concepts and description of simulated vegetation dynamics. *Global Change Biology* **9**: 1543–1566.

**Bonan GB, Patton EG, Finnigan JJ, Baldocchi DD, Harman IN**. **2021**. Moving beyond the incorrect but useful paradigm: Reevaluating big-leaf and multilayer plant canopies to model biosphere-atmosphere fluxes – a review. *Agricultural and Forest Meteorology* **306**: 108435.

**Brando PM**. **2019**. Droughts, Wildfires, and Forest Carbon Cycling: A Pantropical Synthesis | Annual Review of Earth and Planetary Sciences.

**Brando PM, Balch JK, Nepstad DC, Morton DC, Putz FE, Coe MT, Silvério D, Macedo MN, Davidson EA, Nóbrega CC, *et al.*** **2014**. Abrupt increases in Amazonian tree mortality due to drought–fire interactions. *PNAS* **111**: 6347–6352.

**Breshears DD, Fontaine JB, Ruthrof KX, Field JP, Feng X, Burger JR, Law DJ, Kala J, Hardy GESJ**. **2021**. Underappreciated plant vulnerabilities to heat waves. *New Phytologist* **231**: 32–39.

**Buckley TN**. **2021**. Optimal carbon partitioning helps reconcile the apparent divergence between optimal and observed canopy profiles of photosynthetic capacity. *New Phytologist* **230**: 2246–2260.

**Campbell G, Norman J**. **1998**. *An Introduction to Environmental Biophysics*. New York: Springer.

**Carter KR, Cavaleri MA**. **2018**. Within-Canopy Experimental Leaf Warming Induces Photosynthetic Decline Instead of Acclimation in Two Northern Hardwood Species. *Front. For. Glob. Change* **1**.

**Carter KR, Wood TE, Reed SC, Butts KM, Cavaleri MA**. **2021**. Experimental warming across a tropical forest canopy height gradient reveals minimal photosynthetic and respiratory acclimation. *Plant, Cell & Environment* **44**: 2879–2897.

**Casas RR de, Vargas P, Pérez‐Corona E, Manrique E, García‐Verdugo C, Balaguer L**. **2011**. Sun and shade leaves of Olea europaea respond differently to plant size, light availability and genetic variation. *Functional Ecology* **25**: 802–812.

**Cavaleri MA**. **2020**. Cold-blooded forests in a warming world. *New Phytologist* **228**: 1455–1457.

**Cavaleri MA, Oberbauer SF, Clark DB, Clark DA, Ryan MG**. **2010**. Height is more important than light in determining leaf morphology in a tropical forest. *Ecology* **91**: 1730–1739.

**Cavaleri MA, Oberbauer SF, Ryan MG**. **2008**. Foliar and ecosystem respiration in an old-growth tropical rain forest. *Plant, Cell & Environment* **31**: 473–483.

**Cavender-Bares J, Bazzaz FA**. **2000**. Changes in drought response strategies with ontogeny in Quercus rubra: Implications for scaling from seedlings to mature trees. *Oecologia* **124**: 8–18.

**Chazdon RL, Fetcher N**. **1984**. Photosynthetic Light Environments in a Lowland Tropical Rain Forest in Costa Rica. *Journal of Ecology* **72**: 553–564.

**Chen X, Sun J, Wang M, Lyu M, Niklas KJ, Michaletz ST, Zhong Q, Cheng D**. **2020**. The Leaf Economics Spectrum Constrains Phenotypic Plasticity Across a Light Gradient. *Front. Plant Sci.* **11**.

**Chin ARO, Sillett SC**. **2017**. Leaf acclimation to light availability supports rapid growth in tall Picea sitchensis trees. *Tree Physiol* **37**: 1352–1366.

**Christoffersen BO, Gloor M, Fauset S, Fyllas NM, Galbraith DR, Baker R, Kruijt B, Rowland L, Fisher RA, Binks OJ, *et al.*** **2016**. Linking hydraulic traits to tropical forest function in a size-structured and trait-driven model (TFS v.1-Hydro). *Geosci. Model Dev.*: 29.

**Coble AP, Cavaleri MA**. **2014**. Light drives vertical gradients of leaf morphology in a sugar maple (Acer saccharum) forest. *Tree Physiol* **34**: 146–158.

**Coble AP, VanderWall B, Mau A, Cavaleri MA**. **2016**. How vertical patterns in leaf traits shift seasonally and the implications for modeling canopy photosynthesis in a temperate deciduous forest. *Tree Physiology* **36**: 1077–1091.

**Condit R, Watts K, Bohlman SA, Pérez R, Foster RB, Hubbell SP**. **2000**. Quantifying the deciduousness of tropical forest canopies under varying climates. *Journal of Vegetation Science* **11**: 649–658.

**Corlett RT**. **2011**. Impacts of warming on tropical lowland rainforests. *Trends in Ecology & Evolution* **26**: 606–613.

**Cunningham SC, Read J**. **2003**. Do temperate rainforest trees have a greater ability to acclimate to changing temperatures than tropical rainforest trees? *New Phytologist* **157**: 55–64.

**Curtis EM, Knight CA, Leigh A**. **2019**. Intracanopy adjustment of leaf-level thermal tolerance is associated with microclimatic variation across the canopy of a desert tree (Acacia papyrocarpa). *Oecologia* **189**: 37–46.

**Dang QL, Margolis HA, Sy M, Coyea MR, Collatz GJ, Walthall CL**. **1997**. Profiles of photosynthetically active radiation, nitrogen and photosynthetic capacity in the boreal forest: Implications for scaling from leaf to canopy. *Journal of Geophysical Research: Atmospheres* **102**: 28845–28859.

**Daudet FA, Le Roux X, Sinoquet H, Adam B**. **1999**. Wind speed and leaf boundary layer conductance variation within tree crown: Consequences on leaf-to-atmosphere coupling and tree functions. *Agricultural and Forest Meteorology* **97**: 171–185.

**Davis KT, Dobrowski SZ, Holden ZA, Higuera PE, Abatzoglou JT**. **2019a**. Microclimatic buffering in forests of the future: The role of local water balance. *Ecography* **42**: 1–11.

**Davis FW, Synes NW, Fricker GA, McCullough IM, Serra-Diaz JM, Franklin J, Flint AL**. **2019b**. LiDAR-derived topography and forest structure predict fine-scale variation in daily surface temperatures in oak savanna and conifer forest landscapes. *Agricultural and Forest Meteorology* **269-270**: 192–202.

**De Frenne P, Lenoir J, Luoto M, Scheffers BR, Zellweger F, Aalto J, Ashcroft MB, Christiansen DM, Decocq G, Pauw KD, *et al.*** **2021**. Forest microclimates and climate change: Importance, drivers and future research agenda. *Global Change Biology* **27**: 2279–2297.

**De Frenne P, Zellweger F, Rodríguez-Sánchez F, Scheffers BR, Hylander K, Luoto M, Vellend M, Verheyen K, Lenoir J**. **2019**. Global buffering of temperatures under forest canopies. *Nature Ecology & Evolution* **3**: 744–749.

**De Pury DGG, Farquhar GD**. **1997**. Simple scaling of photosynthesis from leaves to canopies without the errors of big-leaf models. *Plant Cell Environ* **20**: 537–557.

**Detto M, Asner GP, Muller-Landau HC, Sonnentag O**. **2015**. Spatial variability in tropical forest leaf area density from multireturn lidar and modeling. *Journal of Geophysical Research: Biogeosciences* **120**: 294–309.

**Dietz J, Leuschner C, Hölscher D, Kreilein H**. **2007**. Vertical patterns and duration of surface wetness in an old-growth tropical montane forest, Indonesia. *Flora - Morphology, Distribution, Functional Ecology of Plants* **202**: 111–117.

**Dong N, Prentice IC, Harrison SP, Song QH, Zhang YP**. **2017**. Biophysical homoeostasis of leaf temperature: A neglected process for vegetation and land-surface modelling. *Global Ecology and Biogeography* **26**: 998–1007.

**Doughty CE, Goulden ML**. **2008**. Are tropical forests near a high temperature threshold? *Journal of Geophysical Research: Biogeosciences* **113**.

**Drake JE, Harwood R, Vårhammar A, Barbour MM, Reich PB, Barton CVM, Tjoelker MG**. **2020**. No evidence of homeostatic regulation of leaf temperature in Eucalyptus parramattensis trees: Integration of CO2 flux and oxygen isotope methodologies. *New Phytologist* **228**: 1511–1523.

**Duffy KA, Schwalm CR, Arcus VL, Koch GW, Liang LL, Schipper LA**. **2021**. How close are we to the temperature tipping point of the terrestrial biosphere? *Science Advances* **7**: eaay1052.

**Duque A, Stevenson PR, Feeley KJ**. **2015**. Thermophilization of adult and juvenile tree communities in the northern tropical Andes. *Proc Natl Acad Sci USA* **112**: 10744–10749.

**Duursma RA, Marshall JD**. **2006**. Vertical canopy gradients in δ13C correspond with leaf nitrogen content in a mixed-species conifer forest. *Trees* **20**: 496–506.

**Fauset S, Freitas HC, Galbraith DR, Sullivan MJP, Aidar MPM, Joly CA, Phillips OL, Vieira SA, Gloor MU**. **2018**. Differences in leaf thermoregulation and water use strategies between three co-occurring Atlantic forest tree species. *Plant, Cell & Environment* **41**: 1618–1631.

**Feeley K, Martinez-Villa J, Perez T, Silva Duque A, Triviño Gonzalez D, Duque A**. **2020**. The Thermal Tolerances, Distributions, and Performances of Tropical Montane Tree Species. *Frontiers in Forests and Global Change* **3**.

**Fisher RA, Koven CD, Anderegg WRL, Christoffersen BO, Dietze MC, Farrior CE, Holm JA, Hurtt GC, Knox RG, Lawrence PJ, *et al.*** **2018**. Vegetation demographics in Earth System Models: A review of progress and priorities. *Global Change Biology* **24**: 35–54.

**Fisher JB, Lee B, Purdy AJ, Halverson GH, Dohlen MB, Cawse-Nicholson K, Wang A, Anderson RG, Aragon B, Arain MA, *et al.*** **2020**. ECOSTRESS: NASA’s Next Generation Mission to Measure Evapotranspiration From the International Space Station. *Water Resources Research* **56**: e2019WR026058.

**Foley JA, Prentice IC, Ramankutty N, Levis S, Pollard D, Sitch S, Haxeltine A**. **1996**. An integrated biosphere model of land surface processes, terrestrial carbon balance, and vegetation dynamics. *Global Biogeochemical Cycles* **10**: 603–628.

**Fredeen AL, Sage RF**. **1999**. Temperature and humidity effects on branchlet gas-exchange in white spruce: An explanation for the increase in transpiration with branchlet temperature. *Trees* **14**: 161–168.

**Friedlingstein P, Cox P, Betts R, Bopp L, von Bloh W, Brovkin V, Cadule P, Doney S, Eby M, Fung I, *et al.*** **2006**. Climate–Carbon Cycle Feedback Analysis: Results from the C4MIP Model Intercomparison. *J. Climate* **19**: 3337–3353.

**Fritts HC**. **1976**. *Tree rings and climate*. London; New York: Academic Press.

**Garcia MN, Ferreira MJ, Ivanov V, dos Santos VAHF, Ceron JV, Guedes AV, Saleska SR, Oliveira RS**. **2021**. Importance of hydraulic strategy trade-offs in structuring response of canopy trees to extreme drought in central Amazon. *Oecologia*.

**Gebauer R, Volařík D, Urban J, Børja I, Nagy NE, Eldhuset TD, Krokene P**. **2015**. Effects of prolonged drought on the anatomy of sun and shade needles in young Norway spruce trees. *Ecol Evol* **5**: 4989–4998.

**Gillerot L, Forrester DI, Bottero A, Rigling A, Lévesque M**. **2020**. Tree Neighbourhood Diversity Has Negligible Effects on Drought Resilience of European Beech, Silver Fir and Norway Spruce. *Ecosystems* **24**: 20–36.

**Gregoriou K, Pontikis K, Vemmos S**. **2007**. Effects of reduced irradiance on leaf morphology, photosynthetic capacity, and fruit yield in olive (Olea europaea L.). *Photosynthetica* **45**: 172–181.

**Greiser C, Ehrlén J, Meineri E, Hylander K**. **2019**. Hiding from the climate: Characterizing microrefugia for boreal forest understory species. *Global Change Biology* **26**: 471–483.

**Griffin KL, Turnbull M, Murthy R**. **2002**. Canopy position affects the temperature response of leaf respiration in Populus deltoides. *New Phytologist* **154**: 609–619.

**Grossiord C, Buckley TN, Cernusak LA, Novick KA, Poulter B, Siegwolf RTW, Sperry JS, McDowell NG**. **2020**. Plant responses to rising vapor pressure deficit. *New Phytologist* **226**: 1550–1566.

**Hadley JL, Smith WK**. **1987**. Influence of Krummholz Mat Microclimate on Needle Physiology and Survival. *Oecologia* **73**: 82–90.

**Hamerlynck E, Knapp AK**. **1996**. Photosynthetic and stomatal responses to high temperature and light in two oaks at the western limit of their range. *Tree Physiology* **16**: 557–565.

**Hanberry BB, Bragg DC, Alexander HD**. **2020**. Open forest ecosystems: An excluded state. *Forest Ecology and Management* **472**: 118256.

**Hanberry BB, Bragg DC, Hutchinson TF**. **2018**. A reconceptualization of open oak and pine ecosystems of eastern North America using a forest structure spectrum. *Ecosphere* **9**: e02431.

**Hansen U, Fiedler B, Rank B**. **2002**. Variation of pigment composition and antioxidative systems along the canopy light gradient in a mixed beech/oak forest: A comparative study on deciduous tree species differing in shade tolerance. *Trees* **16**: 354–364.

**Hardwick SR, Toumi R, Pfeifer M, Turner EC, Nilus R, Ewers RM**. **2015**. The relationship between leaf area index and microclimate in tropical forest and oil palm plantation: Forest disturbance drives changes in microclimate. *Agricultural and Forest Meteorology* **201**: 187–195.

**Harley P, Guenther A, Zimmerman P**. **1996**. Effects of light, temperature and canopy position on net photosynthesis and isoprene emission from sweetgum (Liquidambar styraciflua) leaves. *Tree Physiol* **16**: 25–32.

**Harley P, Guenther A, Zimmerman P**. **1997**. Environmental controls over isoprene emission in deciduous oak canopies. *Tree Physiology* **17**: 705–714.

**Harris NL, Medina E**. **2013**. Changes in leaf properties across an elevation gradient in the Luquillo Mountains, Puerto Rico. *Ecological Bulletins*: 169–180.

**Havaux M, Tardy F**. **1996**. Temperature-dependent adjustment of the thermal stability of photosystem II in vivo: Possible involvement of xanthophyll-cycle pigments. *Planta* **198**: 324–333.

**He L, Chen JM, Gonsamo A, Luo X, Wang R, Liu Y, Liu R**. **2018**. Changes in the Shadow: The Shifting Role of Shaded Leaves in Global Carbon and Water Cycles Under Climate Change. *Geophysical Research Letters* **45**: 5052–5061.

**Hernández GG, Winter K, Slot M**. **2020**. Similar temperature dependence of photosynthetic parameters in sun and shade leaves of three tropical tree species. *Tree Physiol* **40**: 637–651.

**Houter NC, Pons TL**. **2012**. Ontogenetic changes in leaf traits of tropical rainforest trees differing in juvenile light requirement. *Oecologia* **169**: 33–45.

**Huang M, Piao S, Ciais P, Peñuelas J, Wang X, Keenan TF, Peng S, Berry JA, Wang K, Mao J, *et al.*** **2019**. Air temperature optima of vegetation productivity across global biomes. *Nature Ecology & Evolution* **3**: 772–779.

**Hulley G, Shivers S, Wetherley E, Cudd R**. **2019**. New ECOSTRESS and MODIS Land Surface Temperature Data Reveal Fine-Scale Heat Vulnerability in Cities: A Case Study for Los Angeles County, California. *Remote Sensing* **11**: 2136.

**Hurtt GC, Moorcroft PR, And SWP, Levin SA**. **1998**. Terrestrial models and global change: Challenges for the future. *Global Change Biology* **4**: 581–590.

**Ichie T, Inoue Y, Takahashi N, Kamiya K, Kenzo T**. **2016**. Ecological distribution of leaf stomata and trichomes among tree species in a Malaysian lowland tropical rain forest. *J Plant Res* **129**: 625–635.

**IPCC**. **2021**. Climate change widespread, rapid, and intensifying – IPCC — IPCC.

**Ishii HT, Tanabe S, Hiura T**. **2004**. Exploring the Relationships Among Canopy Structure, Stand Productivity, and Biodiversity of Temperate Forest Ecosystems. *for sci* **50**: 342–355.

**Johnston M, Andreu A, Verfaillie J, Baldocchi DD, Moorcroft PR**. **2020**. What Lies Beneath: Vertical Heterogeneity in Vegetation Canopy Temperatures. **2020**: B088–03.

**Jucker T, Hardwick SR, Both S, Elias DMO, Ewers RM, Milodowski DT, Swinfield T, Coomes DA**. **2018**. Canopy structure and topography jointly constrain the microclimate of human-modified tropical landscapes. *Global Change Biology* **24**: 5243–5258.

**Kafuti C, Bourland N, De Mil T, Meeus S, Rousseau M, Toirambe B, Bolaluembe P-C, Ndjele L, Beeckman H**. **2020**. Foliar and Wood Traits Covary along a Vertical Gradient within the Crown of Long-Lived Light-Demanding Species of the Congo Basin Semi-Deciduous Forest. *Forests* **11**: 35.

**Keenan TF, Niinemets Ü**. **2016**. Global leaf trait estimates biased due to plasticity in the shade. *Nature Plants* **3**: 1–6.

**Kenzo T, Inoue Y, Yoshimura M, Yamashita M, Tanaka-Oda A, Ichie T**. **2015**. Height-related changes in leaf photosynthetic traits in diverse Bornean tropical rain forest trees. *Oecologia* **177**: 191–202.

**Kikuzawa K, Lechowicz MJ**. **2006**. Toward Synthesis of Relationships among Leaf Longevity, Instantaneous Photosynthetic Rate, Lifetime Leaf Carbon Gain, and the Gross Primary Production of Forests. *The American Naturalist* **168**: 373–383.

**Kitao M, Kitaoka S, Harayama H, Tobita H, Agathokleous E, Utsugi H**. **2018**. Canopy nitrogen distribution is optimized to prevent photoinhibition throughout the canopy during sun flecks. *Scientific Reports* **8**: 503.

**Koch GW, Amthor JS, Goulden ML**. **1994**. Diurnal patterns of leaf photosynthesis, conductance and water potential at the top of a lowland rain forest canopy in Cameroon: Measurements from the Radeau des Cimes. *Tree Physiology* **14**: 347–360.

**Koike T, Kitao M, Maruyama Y, Mori S, Lei TT**. **2001**. Leaf morphology and photosynthetic adjustments among deciduous broad-leaved trees within the vertical canopy profile. *Tree Physiology* **21**: 951–958.

**Koike F, Syahbuddin**. **1993**. Canopy Structure of a Tropical Rain Forest and the Nature of an Unstratified Upper Layer. *Functional Ecology* **7**: 230–235.

**Konrad W, Katul G, Roth‐Nebelsick A**. **2021**. Leaf temperature and its dependence on atmospheric CO 2 and leaf size. *Geological Journal* **56**: 866–885.

**Kosugi Y, Matsuo N**. **2006**. Seasonal fluctuations and temperature dependence of leaf gas exchange parameters of co-occurring evergreen and deciduous trees in a temperate broad-leaved forest. *Tree Physiology* **26**: 1173–1184.

**Königer M, Harris GC, Virgo A, Winter K**. **1995**. Xanthophyll-Cycle Pigments and Photosynthetic Capacity in Tropical Forest Species: A Comparative Field Study on Canopy, Gap and Understory Plants. *Oecologia* **104**: 280–290.

**Krause A, Pugh TAM, Bayer AD, Li W, Leung F, Bondeau A, Doelman JC, Humpenöder F, Anthoni P, Bodirsky BL, *et al.*** **2018**. Large uncertainty in carbon uptake potential of land-based climate-change mitigation efforts. *Global Change Biology* **24**: 3025–3038.

**Krinner G, Viovy N, Noblet-Ducoudré N de, Ogée J, Polcher J, Friedlingstein P, Ciais P, Sitch S, Prentice IC**. **2005**. A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system. *Global Biogeochemical Cycles* **19**.

**Kumarathunge DP, Medlyn BE, Drake JE, Tjoelker MG, Aspinwall MJ, Battaglia M, Cano FJ, Carter KR, Cavaleri MA, Cernusak LA, *et al.*** **2019b**. Acclimation and adaptation components of the temperature dependence of plant photosynthesis at the global scale. *New Phytol* **222**: 768–784.

**Kumarathunge DP, Medlyn BE, Drake JE, Tjoelker MG, Aspinwall MJ, Battaglia M, Cano FJ, Carter KR, Cavaleri MA, Cernusak LA, *et al.*** **2019a**. Acclimation and adaptation components of the temperature dependence of plant photosynthesis at the global scale. *New Phytol* **222**: 768–784.

**Kunert N, Aparecido LMT, Wolff S, Higuchi N, Santos J dos, Araujo AC de, Trumbore S**. **2017**. A revised hydrological model for the Central Amazon: The importance of emergent canopy trees in the forest water budget. *Agricultural and Forest Meteorology* **239**: 47–57.

**Kusi J, Karsai I**. **2020**. Plastic leaf morphology in three species of Quercus: The more exposed leaves are smaller, more lobated and denser. *Plant Species Biology* **35**: 24–37.

**Laurance WF, Nascimento HEM, Laurance SG, Andrade AC, Fearnside PM, Ribeiro JEL, Capretz RL**. **2006**. Rain Forest Fragmentation and the Proliferation of Successional Trees. *Ecology* **87**: 469–482.

**Law BE, Cescatti A, Baldocchi DD**. **2001**. Leaf area distribution and radiative transfer in open-canopy forests: Implications for mass and energy exchange. *Tree Physiology* **21**: 777–787.

**Legner N, Fleck S, Leuschner C**. **2014**. Within-canopy variation in photosynthetic capacity, SLA and foliar N in temperate broad-leaved trees with contrasting shade tolerance. *Trees* **28**: 263–280.

**Leigh A, Sevanto S, Close JD, Nicotra AB**. **2017**. The influence of leaf size and shape on leaf thermal dynamics: Does theory hold up under natural conditions? *Plant, Cell & Environment* **40**: 237–248.

**Leuzinger S, Körner C**. **2007**. Tree species diversity affects canopy leaf temperatures in a mature temperate forest. *Agricultural and Forest Meteorology* **146**: 29–37.

**Levizou E, Drilias P, Psaras GK, Manetas Y**. **2005**. Nondestructive assessment of leaf chemistry and physiology through spectral reflectance measurements may be misleading when changes in trichome density co-occur. *New Phytologist* **165**: 463–472.

**Liakoura V, Stefanou M, Manetas Y, Cholevas C, Karabourniotis G**. **1997**. Trichome density and its UV-B protective potential are affected by shading and leaf position on the canopy. *Environmental and Experimental Botany* **38**: 223–229.

**Lloyd J, Farquhar GD**. **2008**. Effects of rising temperatures and [CO2] on the physiology of tropical forest trees. *Philos Trans R Soc Lond B Biol Sci* **363**: 1811–1817.

**Lowman M, Rinker HB**. **1995**. Forest Canopies. In: Endeavour.

**Lusk CH, Reich PB, Montgomery RA, Ackerly DD, Cavender-Bares J**. **2008**. Why are evergreen leaves so contrary about shade? *Trends in Ecology & Evolution* **23**: 299–303.

**Maes SL, Perring MP, Depauw L, Bernhardt‐Römermann M, Blondeel H, Brūmelis G, Brunet J, Decocq G, Ouden J den, Govaert S, *et al.*** **2020**. Plant functional trait response to environmental drivers across European temperate forest understorey communities. *Plant Biology* **22**: 410–424.

**Majasalmi T, Rautiainen M**. **2020**. The impact of tree canopy structure on understory variation in a boreal forest. *Forest Ecology and Management* **466**: 118100.

**Marenco RA, Camargo MAB, Antezana-Vera SA, Oliveira MF**. **2017**. Leaf trait plasticity in six forest tree species of central Amazonia. *Photosynthetica* **55**: 679–688.

**Marias DE, Meinzer FC, Still C**. **2017**. Impacts of leaf age and heat stress duration on photosynthetic gas exchange and foliar nonstructural carbohydrates in Coffea arabica. *Ecology and Evolution* **7**: 1297–1310.

**Martin TA, Hinckley TM, Meinzer FC, Sprugel DG**. **1999**. Boundary layer conductance, leaf temperature and transpiration of Abies amabilis branches. *Tree Physiology* **19**: 435–443.

**Mathur S, Jain L, Jajoo A**. **2018**. Photosynthetic efficiency in sun and shade plants. *Photosynt.* **56**: 354–365.

**Matsubara S, Krause GH, Aranda J, Virgo A, Beisel KG, Jahns P, Winter K, Matsubara S, Krause GH, Aranda J, *et al.*** **2009**. Sun-shade patterns of leaf carotenoid composition in 86 species of neotropical forest plants. *Functional Plant Biol.* **36**: 20–36.

**Mau A, Reed S, Wood T, Cavaleri M**. **2018**. Temperate and Tropical Forest Canopies are Already Functioning beyond Their Thermal Thresholds for Photosynthesis. *Forests* **9**: 47.

**McDowell NG, Allen CD, Anderson-Teixeira K, Aukema BH, Bond-Lamberty B, Chini L, Clark JS, Dietze M, Grossiord C, Hanbury-Brown A, *et al.*** **2020**. Pervasive shifts in forest dynamics in a changing world. *Science* **368**: eaaz9463.

**McDowell NG, Bond BJ, Hill L, Ryan MG, Whitehead D**. **2011**. Relationship between tree height and carbon isotope discrimination. In: F.C. Meinzer and U. Niinemets, eds. Size and age related changes in tree structure and function. Springer Publishing, 255–286.

**McGregor IR, Helcoski R, Kunert N, Tepley AJ, Gonzalez-Akre EB, Herrmann V, Zailaa J, Stovall AEL, Bourg NA, McShea WJ, *et al.*** **2021**. Tree height and leaf drought tolerance traits shape growth responses across droughts in a temperate broadleaf forest. *New Phytologist* **231**: 601–616.

**Meakem V, Tepley AJ, Gonzalez-Akre EB, Herrmann V, Muller-Landau HC, Wright SJ, Hubbell SP, Condit R, Anderson-Teixeira KJ**. **2018**. Role of tree size in moist tropical forest carbon cycling and water deficit responses. *New Phytologist* **219**: 947–958.

**Mediavilla S, Escudero A**. **2004**. Stomatal responses to drought of mature trees and seedlings of two co-occurring Mediterranean oaks. *Forest Ecology and Management* **187**: 281–294.

**Mediavilla S, Martín I, Babiano J, Escudero A**. **2019**. Foliar plasticity related to gradients of heat and drought stress across crown orientations in three Mediterranean Quercus species. *PLOS ONE* **14**: e0224462.

**Meehl GA, Tebaldi C**. **2004**. More Intense, More Frequent, and Longer Lasting Heat Waves in the 21st Century. *Science* **305**: 994–997.

**Meinzer FC, Clearwater MJ, Goldstein G**. **2001**. Water transport in trees: Current perspectives, new insights and some controversies. *Environmental and Experimental Botany* **45**: 239–262.

**Meir P, Grace J, Miranda AC**. **2001**. Leaf respiration in two tropical rainforests: Constraints on physiology by phosphorus, nitrogen and temperature. *Functional Ecology* **15**: 378–387.

**Michaletz ST, Weiser MD, McDowell NG, Zhou J, Kaspari M, Helliker BR, Enquist BJ**. **2016**. The energetic and carbon economic origins of leaf thermoregulation. *Nature Plants* **2**: 16129.

**Michaletz ST, Weiser MD, Zhou J, Kaspari M, Helliker BR, Enquist BJ**. **2015**. Plant Thermoregulation: Energetics, Trait–Environment Interactions, and Carbon Economics. *Trends in Ecology & Evolution* **30**: 714–724.

**Millen GGM, Clendon JHM**. **1979**. Leaf Angle: An Adaptive Feature of Sun and Shade Leaves. *Botanical Gazette* **140**: 437–442.

**Miller BD, Carter KR, Reed SC, Wood TE, Cavaleri MA**. **2021**. Only sun-lit leaves of the uppermost canopy exceed both air temperature and photosynthetic thermal optima in a wet tropical forest. *Agricultural and Forest Meteorology* **301-302**: 108347.

**Miller SD, Goulden ML, Hutyra LR, Keller M, Saleska SR, Wofsy SC, Figueira AMS, Rocha HR da, Camargo PB de**. **2011**. Reduced impact logging minimally alters tropical rainforest carbon and energy exchange. *PNAS* **108**: 19431–19435.

**Misson L, Baldocchi DD, Black TA, Blanken PD, Brunet Y, Curiel Yuste J, Dorsey JR, Falk M, Granier A, Irvine MR, *et al.*** **2007**. Partitioning forest carbon fluxes with overstory and understory eddy-covariance measurements: A synthesis based on FLUXNET data. *Agricultural and Forest Meteorology* **144**: 14–31.

**Monson RK, Weraduwage SM, Rosenkranz M, Schnitzler J-P, Sharkey TD**. **2021**. Leaf isoprene emission as a trait that mediates the growth-defense tradeoff in the face of climate stress. *Oecologia*.

**Moorcroft PR, Hurtt GC, Pacala SW**. **2001**. A Method for Scaling Vegetation Dynamics: The Ecosystem Demography Model (ed). *Ecological Monographs* **71**: 557–586.

**Moore G, Orozco G, Aparecido L, Miller G**. **2018**. Upscaling Transpiration in Diverse Forests: Insights from a Tropical Premontane Site. *Ecohydrology* **11**: e1920.

**Muir CD**. **2019**. Tealeaves: An R package for modelling leaf temperature using energy budgets. *AoB PLANTS* **11**.

**Muller-Landau HC, Condit RS, Chave J, Thomas SC, Bohlman SA, Bunyavejchewin S, Davies S, Foster R, Gunatilleke S, Gunatilleke N, *et al.*** **2006**. Testing metabolic ecology theory for allometric scaling of tree size, growth and mortality in tropical forests. *Ecology Letters* **9**: 575–588.

**Muller JD, Rotenberg E, Tatarinov F, Oz I, Yakir D**. **2021**. Evidence for efficient non-evaporative leaf-to-air heat dissipation in a pine forest under drought conditions. *bioRxiv*: 2021.02.01.429145.

**Musselman KN, Margulis SA, Molotch NP**. **2013**. Estimation of solar direct beam transmittance of conifer canopies from airborne LiDAR. *Remote Sensing of Environment* **136**: 402–415.

**Nakamura A, Kitching RL, Cao M, Creedy TJ, Fayle TM, Freiberg M, Hewitt CN, Itioka T, Koh LP, Ma K, *et al.*** **2017**. Forests and Their Canopies: Achievements and Horizons in Canopy Science. *Trends in Ecology & Evolution* **32**: 438–451.

**Niinemets Ü**. **1998**. Adjustment of foliage structure and function to a canopy light gradient in two co-existing deciduous trees. Variability in leaf inclination angles in relation to petiole morphology. *Trees* **12**: 446–451.

**Niinemets Ü**. **2007b**. Photosynthesis and resource distribution through plant canopies. *Plant, Cell & Environment* **30**: 1052–1071.

**Niinemets Ü**. **2007a**. Photosynthesis and resource distribution through plant canopies. *Plant, Cell & Environment* **30**: 1052–1071.

**Niinemets Ü**. **2010**. Responses of forest trees to single and multiple environmental stresses from seedlings to mature plants: Past stress history, stress interactions, tolerance and acclimation. *Forest Ecology and Management* **260**: 1623–1639.

**Niinemets Ü**. **2016**. Leaf age dependent changes in within-canopy variation in leaf functional traits: A meta-analysis. *J Plant Res* **129**: 313–338.

**Niinemets Ü, Arneth A, Kuhn U, Monson RK, Peñuelas J, Staudt M**. **2010**. The emission factor of volatile isoprenoids: Stress, acclimation, and developmental responses. *Biogeosciences* **7**: 2203–2223.

**Niinemets Ü, Bilger W, Kull O, Tenhunen JD**. **1998**. Acclimation to high irradiance in temperate deciduous trees in the field: Changes in xanthophyll cycle pool size and in photosynthetic capacity along a canopy light gradient. *Plant, Cell & Environment* **21**: 1205–1218.

**Niinemets Ü, Keenan TF, Hallik L**. **2015a**. A worldwide analysis of within-canopy variations in leaf structural, chemical and physiological traits across plant functional types. *New Phytologist* **205**: 973–993.

**Niinemets Ü, Kull O, Tenhunen JD**. **2004a**. Within-canopy variation in the rate of development of photosynthetic capacity is proportional to integrated quantum flux density in temperate deciduous trees. *Plant, Cell & Environment* **27**: 293–313.

**Niinemets Ü, Kull O, Tenhunen JD**. **2015b**. Variability in Leaf Morphology and Chemical Composition as a Function of Canopy Light Environment in Coexisting Deciduous Trees. *International Journal of Plant Sciences*.

**Niinemets Ü, Oja V, Kull O**. **1999**. Shape of leaf photosynthetic electron transport versus temperature response curve is not constant along canopy light gradients in temperate deciduous trees. *Plant, Cell & Environment* **22**: 1497–1513.

**Niinemets Ü, Sonninen E, Tobias M**. **2004b**. Canopy gradients in leaf intercellular CO2 mole fractions revisited: Interactions between leaf irradiance and water stress need consideration. *Plant, Cell & Environment* **27**: 569–583.

**Niinemets Ü, Sun Z**. **2015**. How light, temperature, and measurement and growth [CO2] interactively control isoprene emission in hybrid aspen. *J Exp Bot* **66**: 841–851.

**Niinemets Ü, Valladares F**. **2004**. Photosynthetic Acclimation to Simultaneous and Interacting Environmental Stresses Along Natural Light Gradients: Optimality and Constraints. *Plant Biology* **6**: 254–268.

**Novick KA, Ficklin DL, Stoy PC, Williams CA, Bohrer G, Oishi AC, Papuga SA, Blanken PD, Noormets A, Sulman BN, *et al.*** **2016**. The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. *Nature Climate Change* **6**: 1023–1027.

**O’Sullivan OS, Heskel MA, Reich PB, Tjoelker MG, Weerasinghe LK, Penillard A, Zhu L, Egerton JJG, Bloomfield KJ, Creek D, *et al.*** **2017**. Thermal limits of leaf metabolism across biomes. *Global Change Biology* **23**: 209–223.

**Oishi AC, Miniat CF, Novick KA, Brantley ST, Vose JM, Walker JT**. **2018**. Warmer temperatures reduce net carbon uptake, but do not affect water use, in a mature southern Appalachian forest. *Agricultural and Forest Meteorology* **252**: 269–282.

**Oldham AR, Sillett SC, Tomescu AMF, Koch GW**. **2010**. The hydrostatic gradient, not light availability, drives height-related variation in Sequoia sempervirens (Cupressaceae) leaf anatomy. *American Journal of Botany* **97**: 1087–1097.

**Olson ME, Soriano D, Rosell JA, Anfodillo T, Donoghue MJ, Edwards EJ, León-Gómez C, Dawson T, Martínez JJC, Castorena M, *et al.*** **2018**. Plant height and hydraulic vulnerability to drought and cold. *PNAS* **115**: 7551–7556.

**Ozanne CMP, Anhuf D, Boulter SL, Keller M, Kitching RL, Körner C, Meinzer FC, Mitchell AW, Nakashizuka T, Dias PLS, *et al.*** **2003**. Biodiversity Meets the Atmosphere: A Global View of Forest Canopies. *Science* **301**: 183–186.

**Panditharathna PAKAK, Singhakumara BMP, Griscom HP, Ashton MS**. **2008**. Change in leaf structure in relation to crown position and size class for tree species within a Sri Lankan tropical rain forest. *Botany* **86**: 633–640.

**Parker GG, Davis MM, Chapotin SM**. **2002**. Canopy light transmittance in Douglas-fir–western hemlock stands. *Tree Physiol* **22**: 147–157.

**Parker GG, Fitzjarrald DR, Gonçalves Sampaio IC**. **2019**. Consequences of environmental heterogeneity for the photosynthetic light environment of a tropical forest. *Agricultural and Forest Meteorology* **278**: 107661.

**Parker GG, O’Neill JP, work(s): DHR**. **1989**. Vertical Profile and Canopy Organization in a Mixed Deciduous Forest. *Vegetatio* **85**: 1–11.

**Parker GG, Tibbs DJ**. **2004**. Structural Phenology of the Leaf Community in the Canopy of a Liriodendron tulipifera L. Forest in Maryland, USA. : 11.

**Pau S, Detto M, Kim Y, Still CJ**. **2018**. Tropical forest temperature thresholds for gross primary productivity. *Ecosphere* **9**: e02311.

**Perez TM, Feeley KJ**. **2018**. Increasing Humidity Threatens Tropical Rainforests. *Front. Ecol. Evol.* **6**: 68.

**Perez TM, Feeley KJ**. **2020**. Photosynthetic heat tolerances and extreme leaf temperatures. *Functional Ecology* **34**: 2236–2245.

**Poorter L, Kwant R, Hernández R, Medina E, Werger MJA**. **2000**. Leaf optical properties in Venezuelan cloud forest trees. *Tree Physiology* **20**: 519–526.

**Poorter L, Oberbauer SF, Clark DB**. **1995**. Leaf Optical Properties Along a Vertical Gradient in a Tropical Rain Forest Canopy in Costa Rica. *American Journal of Botany* **82**: 1257–1263.

**Pörtner H-O, Scholes RJ, Agard J, Archer E, Arneth A, Bai X, Barnes D, Burrows M, Chan L, Cheung WL(William), *et al.*** **2021**. Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change.

**Rambo TR, North MP**. **2009**. Canopy microclimate response to pattern and density of thinning in a Sierra Nevada forest. *Forest Ecology and Management* **257**: 435–442.

**Rey-Sánchez A, Slot M, Posada J, Kitajima K**. **2016**. Spatial and seasonal variation in leaf temperature within the canopy of a tropical forest. *Climate Research* **71**: 75–89.

**Rijkers T, Pons TL, Bongers F**. **2000**. The effect of tree height and light availability on photosynthetic leaf traits of four neotropical species differing in shade tolerance. *Functional Ecology* **14**: 77–86.

**Roberts J, Cabral OMR, Aguiar LFD**. **1990b**. Stomatal and Boundary-Layer Conductances in an Amazonian terra Firme Rain Forest. *The Journal of Applied Ecology* **27**: 336.

**Roberts J, Cabral OMR, Aguiar LFD**. **1990a**. Stomatal and Boundary-Layer Conductances in an Amazonian terra Firme Rain Forest. *The Journal of Applied Ecology* **27**: 336.

**Rohde RA, Hausfather Z**. **2020**. The Berkeley Earth Land/Ocean Temperature Record. *Earth Syst. Sci. Data* **12**: 3469–3479.

**Rollinson CR, Alexander MR, Dye AW, Moore DJP, Pederson N, Trouet V**. **2020**. Climate sensitivity of understory trees differs from overstory trees in temperate mesic forests. *Ecology* **102**: e03264.

**Rozendaal DMA, Hurtado VH, Poorter L**. **2006**. Plasticity in leaf traits of 38 tropical tree species in response to light; relationships with light demand and adult stature. *Functional Ecology* **20**: 207–216.

**Ruehr NK, Gast A, Weber C, Daub B, Arneth A**. **2016**. Water availability as dominant control of heat stress responses in two contrasting tree species. *Tree Physiol* **36**: 164–178.

**Sack L, Cowan PD, Jaikumar N, Holbrook NM**. **2003**. The “hydrology” of leaves: Co-ordination of structure and function in temperate woody species. *Plant, Cell & Environment* **26**: 1343–1356.

**Sack L, Melcher PJ, Liu WH, Middleton E, Pardee T**. **2006**. How strong is intracanopy leaf plasticity in temperate deciduous trees? *American Journal of Botany* **93**: 829–839.

**Sack L, Scoffoni C**. **2013**. Leaf venation: Structure, function, development, evolution, ecology and applications in the past, present and future. *New Phytologist* **198**: 983–1000.

**Sage RF, Kubien DS**. **2007**. The temperature response of C3 and C4 photosynthesis. *Plant, Cell & Environment* **30**: 1086–1106.

**Sanches MC, Ribeiro SP, Dalvi VC, Barbosa da Silva Junior M, Caldas de Sousa H, Pires de Lemos-Filho J**. **2010**. Differential leaf traits of a neotropical tree Cariniana legalis (Mart.) Kuntze (Lecythidaceae): Comparing saplings and emergent trees. *Trees* **24**: 79–88.

**Scafaro AP, Fan Y, Posch BC, Garcia A, Coast O, Atkin OK**. **2021**. Responses of leaf respiration to heatwaves. *Plant, Cell & Environment* **44**: 2090–2101.

**Scartazza A, Di Baccio D, Bertolotto P, Gavrichkova O, Matteucci G**. **2016**. Investigating the European beech (Fagus sylvatica L.) Leaf characteristics along the vertical canopy profile: Leaf structure, photosynthetic capacity, light energy dissipation and photoprotection mechanisms. *Tree Physiol* **36**: 1060–1076.

**Scheffers B, Edwards D, Diesmos A, Williams S, Evans T**. **2013**. Microhabitats reduce animal’s exposure to climate extremes. *Global change biology* **20**.

**Schimel D, Hargrove W, Hoffman F, MacMahon J**. **2007**. NEON: A hierarchically designed national ecological network. *Frontiers in Ecology and the Environment* **5**: 59–59.

**Schymanski SJ, Or D, Zwieniecki M**. **2013**. Stomatal Control and Leaf Thermal and Hydraulic Capacitances under Rapid Environmental Fluctuations. *PLOS ONE* **8**: e54231.

**Sharkey TD**. **2005**. Effects of moderate heat stress on photosynthesis: Importance of thylakoid reactions, rubisco deactivation, reactive oxygen species, and thermotolerance provided by isoprene. *Plant, Cell & Environment* **28**: 269–277.

**Sharkey TD, Monson RK**. **2014**. The future of isoprene emission from leaves, canopies and landscapes. *Plant, Cell & Environment* **37**: 1727–1740.

**Sharkey TD, Wiberley AE, Donohue AR**. **2008**. Isoprene Emission from Plants: Why and How. *Annals of Botany* **101**: 5–18.

**Shugart HH, Wang B, Fischer R, Ma J, Fang J, Yan X, Huth A, Armstrong AH**. **2018**. Gap models and their individual-based relatives in the assessment of the consequences of global change. *Environ. Res. Lett.* **13**: 033001.

**Sitch S, Smith B, Prentice IC, Arneth A, Bondeau A, Cramer W, Kaplan JO, Levis S, Lucht W, Sykes MT, *et al.*** **2003**. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biology* **9**: 161–185.

**Slot M, Cala D, Aranda J, Virgo A, Michaletz ST, Winter K**. **2021a**. Leaf heat tolerance of 147 tropical forest species varies with elevation and leaf functional traits, but not with phylogeny. *Plant Cell Environ* **44**: 2414–2427.

**Slot M, Kitajima K**. **2015**. General patterns of acclimation of leaf respiration to elevated temperatures across biomes and plant types. *Oecologia* **177**: 885–900.

**Slot M, Krause GH, Krause B, Hernández GG, Winter K**. **2019**. Photosynthetic heat tolerance of shade and sun leaves of three tropical tree species. *Photosynth Res* **141**: 119–130.

**Slot M, Rifai SW, Winter K**. **2021b**. Photosynthetic plasticity of a tropical tree species, *Tabebuia* *Rosea* , in response to elevated temperature and [ CO 2 ]. *Plant Cell Environ*: pce.14049.

**Slot M, Winter K**. **2017**. In situ temperature response of photosynthesis of 42 tree and liana species in the canopy of two Panamanian lowland tropical forests with contrasting rainfall regimes. *New Phytologist* **214**: 1103–1117.

**Smith WK, Carter GA**. **1988**. Shoot Structural Effects on Needle Temperatures and Photosynthesis in Conifers. *American Journal of Botany* **75**: 496–500.

**Smith B, Prentice IC, Sykes MT**. **2001**. Representation of vegetation dynamics in the modelling of terrestrial ecosystems: Comparing two contrasting approaches within European climate space. *Global Ecology and Biogeography* **10**: 621–637.

**Smith MN, Stark SC, Taylor TC, Ferreira ML, de Oliveira E, Restrepo-Coupe N, Chen S, Woodcock T, Figueira M, de Camargo PB, *et al.*** **2019a**. Seasonal and drought-related changes in leaf area profiles depend on height and light environment in an Amazon forest. *New Phytologist*: 37.

**Smith MN, Stark SC, Taylor TC, Ferreira ML, Oliveira E de, Restrepo‐Coupe N, Chen S, Woodcock T, Santos DB dos, Alves LF, *et al.*** **2019b**. Seasonal and drought-related changes in leaf area profiles depend on height and light environment in an Amazon forest. *New Phytologist* **222**: 1284–1297.

**Smith MN, Taylor TC, van Haren J, Rosolem R, Restrepo-Coupe N, Adams J, Wu J, de Oliveira RC, da Silva R, de Araujo AC, *et al.*** **2020**. Empirical evidence for resilience of tropical forest photosynthesis in a warmer world. *Nature Plants* **6**: 1225–1230.

**Song Q, Sun C, Deng Y, Bai H, Zhang Y, Yu H, Zhang J, Sha L, Zhou W, Liu Y**. **2020**. Tree Surface Temperature in a Primary Tropical Rain Forest. *Atmosphere* **11**: 798.

**Stark SC, Breshears DD, Aragón S, Villegas JC, Law DJ, Smith MN, Minor DM, Assis RL de, Almeida DRA de, Oliveira G de, *et al.*** **2020**. Reframing tropical savannization: Linking changes in canopy structure to energy balance alterations that impact climate. *Ecosphere* **11**: e03231.

**Staudt K, Serafimovich A, Siebicke L, Pyles RD, Falge E**. **2011**. Vertical structure of evapotranspiration at a forest site (a case study). *Agricultural and Forest Meteorology* **151**: 709–729.

**Stovall AEL, Shugart H, Yang X**. **2019**. Tree height explains mortality risk during an intense drought. *Nature Communications* **10**: 4385.

**Sullivan MJP, Lewis SL, Affum-Baffoe K, Castilho C, Costa F, Sanchez AC, Ewango CEN, Hubau W, Marimon B, Monteagudo-Mendoza A, *et al.*** **2020**. Long-term thermal sensitivity of Earth’s tropical forests. *Science* **368**: 869–874.

**Šimpraga M, Verbeeck H, Bloemen J, Vanhaecke L, Demarcke M, Joó E, Pokorska O, Amelynck C, Schoon N, Dewulf J, *et al.*** **2013**. Vertical canopy gradient in photosynthesis and monoterpenoid emissions: An insight into the chemistry and physiology behind. *Atmospheric Environment* **80**: 85–95.

**Tan Z-H, Zeng J, Zhang Y-J, Slot M, Gamo M, Hirano T, Kosugi Y, da Rocha HR, Saleska SR, Goulden ML, *et al.*** **2017**. Optimum air temperature for tropical forest photosynthesis: Mechanisms involved and implications for climate warming. *Environ. Res. Lett.* **12**: 054022.

**Taylor TC, McMahon SM, Smith MN, Boyle B, Violle C, Haren J van, Simova I, Meir P, Ferreira LV, Camargo PB de, *et al.*** **2018**. Isoprene emission structures tropical tree biogeography and community assembly responses to climate. *New Phytologist* **220**: 435–446.

**Taylor TC, Smith MN, Slot M, Feeley KJ**. **2019**. The capacity to emit isoprene differentiates the photosynthetic temperature responses of tropical plant species. *Plant Cell Environ* **42**: 2448–2457.

**Taylor TC, Wisniewski WT, Alves EG, Oliveira RC de, Saleska SR**. **2021**. A new field instrument for leaf volatiles reveals an unexpected vertical profile of isoprenoid emission capacities in a tropical forest. *bioRxiv*: 2021.02.15.431157.

**Terborgh J**. **1985**. The Vertical Component of Plant Species Diversity in Temperate and Tropical Forests. *The American Naturalist* **126**: 760–776.

**Thomas SC, Winner WE**. **2002**. Photosynthetic differences between saplings and adult trees: An integration of field results by meta-analysis. *Tree Physiology* **22**: 117–127.

**Tibbitts TW**. **1979**. Humidity and Plants. *BioScience* **29**: 358–363.

**Tiwari R, Gloor E, Cruz WJA da, Marimon BS, Marimon-Junior BH, Reis SM, Souza IA de, Krause HG, Slot M, Winter K, *et al.*** **2021**. Photosynthetic quantum efficiency in south-eastern Amazonian trees may be already affected by climate change. *Plant, Cell & Environment* **44**: 2428–2439.

**Trenberth KE, Dai A, van der Schrier G, Jones PD, Barichivich J, Briffa KR, Sheffield J**. **2014**. Global warming and changes in drought. *Nature Clim Change* **4**: 17–22.

**Trouillier M, van der Maaten-Theunissen M, Scharnweber T, Würth D, Burger A, Schnittler M, Wilmking M**. **2018**. Size matters—a comparison of three methods to assess age- and size-dependent climate sensitivity of trees. *Trees* **33**: 183–192.

**Turnbull MH, Whitehead D, Tissue DT, Schuster WSF, Brown KJ, Griffin KL**. **2003**. Scaling foliar respiration in two contrasting forest canopies. *Functional Ecology* **17**: 101–114.

**Tymen B, Vincent G, Courtois EA, Heurtebize J, Dauzat J, Marechaux I, Chave J**. **2017**. Quantifying micro-environmental variation in tropical rainforest understory at landscape scale by combining airborne LiDAR scanning and a sensor network. *Annals of Forest Science* **74**: 32.

**Urban O, Kosvancová M, Marek MV, Lichtenthaler HK**. **2007**. Induction of photosynthesis and importance of limitations during the induction phase in sun and shade leaves of five ecologically contrasting tree species from the temperate zone. *Tree Physiol* **27**: 1207–1215.

**van de Weg MJ, Meir P, Grace J, Ramos GD**. **2012**. Photosynthetic parameters, dark respiration and leaf traits in the canopy of a Peruvian tropical montane cloud forest. *Oecologia* **168**: 23–34.

**Van Wittenberghe S, Adriaenssens S, Staelens J, Verheyen K, Samson R**. **2012**. Variability of stomatal conductance, leaf anatomy, and seasonal leaf wettability of young and adult European beech leaves along a vertical canopy gradient. *Trees* **26**: 1427–1438.

**Vårhammar A, Wallin G, McLean CM, Dusenge ME, Medlyn BE, Hasper TB, Nsabimana D, Uddling J**. **2015**. Photosynthetic temperature responses of tree species in Rwanda: Evidence of pronounced negative effects of high temperature in montane rainforest climax species. *New Phytologist* **206**: 1000–1012.

**Vogel S**. **1968**. "Sun Leaves" and "Shade Leaves": Differences in Convective Heat Dissipation. *Ecology* **49**: 1203–1204.

**von Arx G, Dobbertin M, Rebetez M**. **2012**. Spatio-temporal effects of forest canopy on understory microclimate in a long-term experiment in Switzerland. *Agricultural and Forest Meteorology* **166-167**: 144–155.

**Way DA**. **2019**. Just the right temperature. *Nat Ecol Evol* **3**: 718–719.

**Way DA, Pearcy RW**. **2012**. Sunflecks in trees and forests: From photosynthetic physiology to global change biology. *Tree Physiol* **32**: 1066–1081.

**Weerasinghe LK, Creek D, Crous KY, Xiang S, Liddell MJ, Turnbull MH, Atkin OK**. **2014**. Canopy position affects the relationships between leaf respiration and associated traits in a tropical rainforest in Far North Queensland. *Tree Physiol* **34**: 564–584.

**Woodward FI, Lomas MR**. **2004**. Vegetation dynamics – simulating responses to climatic change. *Biological Reviews* **79**: 643–670.

**Wright IJ, Reich PB, Westoby M, Ackerly DD, Baruch Z, Bongers F, Cavender-Bares J, Chapin T, Cornelissen JHC, Diemer M, *et al.*** **2004**. The worldwide leaf economics spectrum. *Nature* **428**: 821–827.

**Wu J, Albert LP, Lopes AP, Restrepo-Coupe N, Hayek M, Wiedemann KT, Guan K, Stark SC, Christoffersen B, Prohaska N, *et al.*** **2016**. Leaf development and demography explain photosynthetic seasonality in Amazon evergreen forests. *Science* **351**: 972–976.

**Wyka TP, Oleksyn J, Żytkowiak R, Karolewski P, Jagodziński AM, Reich PB**. **2012**. Responses of leaf structure and photosynthetic properties to intra-canopy light gradients: A common garden test with four broadleaf deciduous angiosperm and seven evergreen conifer tree species. *Oecologia* **170**: 11–24.

**Xu C-Y, Griffin KL**. **2006**. Seasonal variation in the temperature response of leaf respiration in Quercus rubra: Foliage respiration and leaf properties. *Functional Ecology* **20**: 778–789.

**Yang PC, Black TA, Neumann HH, Novak MD, Blanken PD**. **1999**. Spatial and temporal variability of CO2 concentration and flux in a boreal aspen forest. *Journal of Geophysical Research: Atmospheres* **104**: 27653–27661.

**Zaragoza-Castells J, Sánchez-Gómez D, Hartley IP, Matesanz S, Valladares F, Lloyd J, Atkin OK**. **2008**. Climate-dependent variations in leaf respiration in a dry-land, low productivity Mediterranean forest: The importance of acclimation in both high-light and shaded habitats. *Functional Ecology* **22**: 172–184.

**Zaragoza-Castells J, Sánchez-Gómez D, Valladares F, Hurry V, Atkin OK**. **2007**. Does growth irradiance affect temperature dependence and thermal acclimation of leaf respiration? Insights from a Mediterranean tree with long-lived leaves. *Plant Cell Environ* **30**: 820–833.

**Zellweger F, Coomes D, Lenoir J, Depauw L, Maes SL, Wulf M, Kirby KJ, Brunet J, Kopecký M, Máliš F, *et al.*** **2019**. Seasonal drivers of understorey temperature buffering in temperate deciduous forests across Europe (A Algar, Ed.). *Global Ecology and Biogeography* **28**: 1774–1786.

**Zellweger F, De Frenne P, Lenoir J, Vangansbeke P, Verheyen K, Bernhardt-Römermann M, Baeten L, Hédl R, Berki I, Brunet J, *et al.*** **2020**. Forest microclimate dynamics drive plant responses to warming. *Science* **368**: 772–775.

**Zhang J-L, Poorter L, Hao G-Y, Cao K-F**. **2012**. Photosynthetic thermotolerance of woody savanna species in China is correlated with leaf life span. *Annals of Botany* **110**: 1027–1033.

**Zhou H, Xu M, Pan H, Yu X**. **2015**. Leaf-age effects on temperature responses of photosynthesis and respiration of an alpine oak, Quercus aquifolioides, in southwestern China. *Tree Physiology* **35**: 1236–1248.

**Zhu L, Bloomfield KJ, Hocart CH, Egerton JJG, O’Sullivan OS, Penillard A, Weerasinghe LK, Atkin OK**. **2018**. Plasticity of photosynthetic heat tolerance in plants adapted to thermally contrasting biomes. *Plant, Cell & Environment* **41**: 1251–1262.

**Zweifel R, Bohm JP, Hasler R**. **2002**. Midday stomatal closure in Norway spruce–reactions in the upper and lower crown. *Tree Physiology* **22**: 1125–1136.

**Zwieniecki MA, Boyce CK, Holbrook NM**. **2004**. Hydraulic limitations imposed by crown placement determine final size and shape of Quercus rubra L. leaves. *Plant, Cell & Environment* **27**: 357–365.