Supporting Information: Thermal sensitivity across forest vertical profiles: patterns, mechanisms, and ecological implications

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

*be sure to cite Schimel et al. (2007).*

METHODS ON NEON ANALYSIS GO HERE. Google doc: <https://docs.google.com/document/d/1HdPa7X5AMrEwfLjazGMU92uTYMc6pObh/edit#heading=h.gjdgxs>

see [Issue 2](https://github.com/EcoClimLab/vertical-thermal-review/issues/2) , [issue 20](https://github.com/EcoClimLab/vertical-thermal-review/issues/20)

*Note on interpreting* :

Vegetation temperature () is measured using infrared sensors that integrate across both leaves and woody vegetation. Leaf and branch temperatures often differ substantially; for instance, exposed tropical tree bark can be much warmer than leaves (Pau *et al.*, 2018; Johnston *et al.*, 2020; Still *et al.*, 2021). Thus, vegetation temperature () does not always equal or approximate , particularly in settings where leaf area is low relative to woody vegetation (i.e., low-LAI ecosystems and understories).

# Methods S2. Methods for leaf energy balance modeling

Energy balance for a typical overstory sun leaf and understory shade leaf were modeled in the R package *Tleaves* (Muir, 2019), parameterized for *Quercus rubra* L. leaves at Harvard Forest, MA, USA (\*\*GEOGRAPHIC COORDINATES). Parameters are presented in Table S2.

*Describe where you came up with all the parameters:*

* micromet from NEON (explain exactly what you used)
* leaf characteristic dimension, was measured on *Quercus rubra* sun and shade leaf,
* stomatal conductance measurements were referred from Tleaves typical sun and shade measurements (Muir, 2019)

For drought scenario, biophysical variables were parameterized similar to normal scenario using Harvard NEON data. Overstory drought PAR values reflect maximum observed Harvard NEON PAR and understory drought reflect 50% increased PAR of understory normal value. Leaf trait measurements for leaf width is the same as normal scenario, stomatal conductance is kept constant at a minimum value of 0.01 umol/m^2/s/Pa for both positions. In each visual, all variables are constant (Biophysical Constants table) except for the independent variable that represents minimum - maximum range.

# Methods S3. Methods for literature review

## Identification of relevant studies

Relevant studies were searched in the databases: ISI Web of Science, Smithsonian online library and Google Scholar, using the following key terms: (leaf traits OR foliar traits) AND (inter-canopy OR intra-canopy OR canopy height) AND (e.g. chlorophyll OR e.g. LMA OR stomatal conductance); (leaf temperature and metabolism OR leaf thermal sensitivity OR leaf thermal tolerance OR leaf traits OR foliar traits) AND (within-canopy OR intra-canopy OR sun shade OR canopy height OR canopy gradient OR canopy profile OR canopy position) AND (temperate forests OR boreal forest OR conifer OR savanna OR tropical); (leaf\* temperature\* and metabolism OR leaf thermal\* sensitivity OR leaf thermal tolerance OR leaf\* traits OR foliar\* traits) AND (within-canopy OR intra-canopy OR sun shade OR canopy\* height OR canopy gradient OR canopy profile) AND (temperate forests OR boreal forest OR conifer OR savanna OR tropical).

in Google Scholar, 600 articles were screened, using the key terms—(leaf temperature and metabolism OR leaf thermal sensitivity OR leaf thermal tolerance OR leaf traits OR foliar traits) AND (within-canopy OR intra-canopy OR sun shade OR canopy height OR canopy gradient OR canopy profile OR canopy position) AND (temperate forests OR boreal forest OR conifer OR savanna OR tropical). After screening the title and reading the abstract, 185 articles were most relevant. Herbaceous plant studies and seedling studies were excluded. These articles were added into Zotero folders: Leaf traits; Leaf Metabolism and Processes, accordingly, for further careful reading.

Similar search was conducted with the Smithsonian online library with the key terms— (leaf traits OR foliar traits) AND (inter-canopy OR intra-canopy OR canopy height) AND (e.g. chlorophyll OR e.g. LMA OR stomatal conductance)— provided most relevant results among the set of keywords mentioned above, with the field refine function that included botany, ecology, biology, environmental sciences, and forestry. Out of 150 relevant articles screened, 26 were most relevant after screening the title and reading the abstract, out of which 22 were already acquired through Google scholar search, 4 new articles were added to the folder.

For ISI Web of Science, search the key terms—(leaf\* temperature\* and metabolism OR leaf thermal\* sensitivity OR leaf thermal tolerance OR leaf\* traits OR foliar\* traits) AND (within-canopy OR intra-canopy OR sun shade OR canopy\* height OR canopy gradient OR canopy profile) AND (temperate forests OR boreal forest OR conifer OR savanna OR tropical)— yielded 410 relevant results, 37 were most relevant after screening the title and reading the abstract, out of which 24 were already acquired through the above process, 13 new articles were added to Zotero folders.

Through the above process, 202 articles were acquired into Zotero folders. The articles were tagged after careful reading of each as ‘added to the table’, ‘irrelevant to the table, but relevant to the review’ (with a note on the reason), ‘irrelevant to the table and the review’ (with a note on the reason for exclusion). Articles that were not yet carefully read were tagged ‘yet to read’, which will be tagged as one of the above after reading. Articles shared by co-authors and references mentioned in other studies collectively were ~>32 studies. So far 40 relevant articles are added into the tables

## Criteria for inclusion

**this is outlined** [**here**](https://github.com/EcoClimLab/vertical-thermal-review/blob/master/Lit_Review/Methods%20for%20Systematic%20review%20for%20the%20tables.docx)**. Section needs to be written.**

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

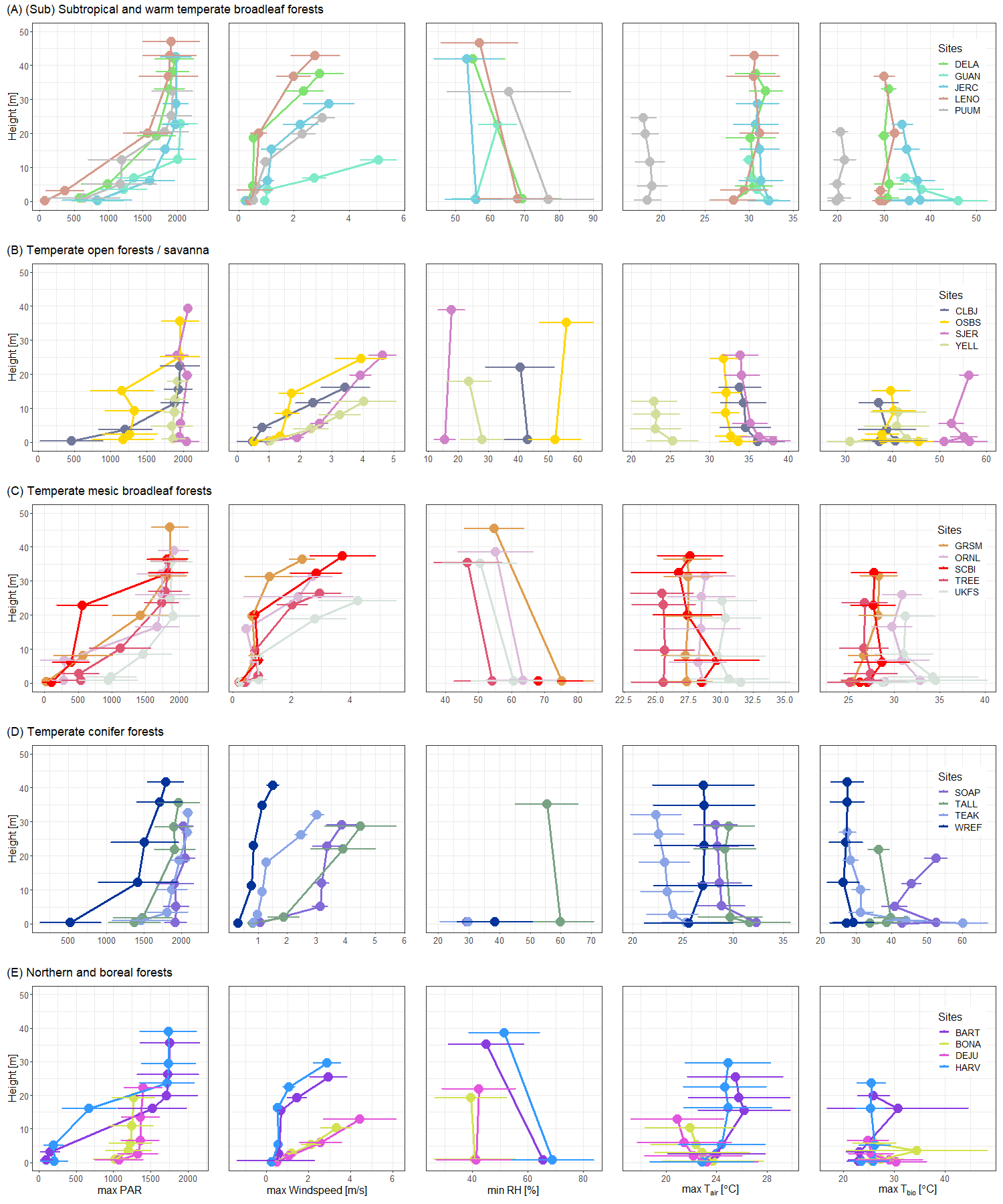
| site code | site name | US state | latitude | longitude | forest type\* |
| --- | --- | --- | --- | --- | --- |
| BART | Bartlett Experimental Forest Tower | NH | 44.06389 | -71.28737 | Eastern Deciduous Forest, Boreal ecotone |
| BONA | Bonanza Creek | AK | 65.15401 | -147.50258 | Spruce forest on permafrost |
| CLBJ | Lyndon B. Johnson National Grassland | TX | 33.40123 | -97.57000 | A mosaic of the Cross Timbers forest (oak-dominated) and grasslands |
| DEJU | Delta Junction | AK | 63.88112 | -145.75136 | Spruce forest on non-permafrost land |
| DELA | Dead Lake site | AL | 32.54173 | -87.80388 | Mixed closed-canopy deciduous hardwood forest including cypress, red oak, black gum, shagbark hickory, oaks and green ash |
| GRSM | Great Smoky Mountains National Park, Twin Creeks | TN | 35.68896 | -83.50195 | Hardwood deciduous forest dominated by oaks and maples |
| GUAN | Guanica Forest | PR | 17.96955 | -66.86870 | Subtropical dry seasonal forest, dense closed canopy |
| HARV | Harvard Forest Tower | MA | 42.53690 | -72.17266 | Eastern Deciduous forest |
| JERC | Jones Ecological Research Center | GA | 31.19484 | -84.46861 | Mixed longleaf pine/hardwood forest |
| LENO | Lenoir Landing | AL | 31.85388 | -88.16122 | Oak-dominant closed-canopy hardwood forest |
| MLBS | Mountain Lake Biological Station | VA | 37.37828 | -80.52484 | Eastern Deciduous Forest dominated by Oak |
| ORNL | Oak Ridge | TN | 35.96412 | -84.28260 | Eastern Uplands Deciduous forest |
| OSBS | Ordway-Swisher Biological Station | FL | 29.68928 | -81.99343 | Open Longleaf-pine forest |
| PUUM | Pu‘u Maka‘ala Natural Area Reserve | HI | 19.55309 | -155.31731 | Metrosideros polymorpha-dominated tropical montane forest |
| SCBI | Smithsonian Conservation Biology Institute | VA | 38.89292 | -78.13949 | Tulip popular and oak dominated closed forest |
| SERC | Smithsonian Environmental Research Center | MD | 38.89013 | -76.56001 | Hardwood deciduous forest dominant by tulip popular, oak and ash |
| SJER | San Joaquin Experimental Range | CA | 37.10878 | -119.73228 | Oak-dominated woodland savanna |
| SOAP | Soaproot Saddle | CA | 37.03337 | -119.26219 | Pine-dominated forest |
| STEI | Steigerwaldt Land Services | WI | 45.50894 | -89.58637 | Aspen dominated regenerating forest |
| TALL | Talladega National Forest | AL | 32.95046 | -87.39327 | Restored longleaf pine forest |
| TEAK | Lower Teakettle | CA | 37.00583 | -119.00602 | Mixed coniferous forest dominated by red fir, ponderosa and Jeffery pine, white fir, etc. |
| TREE | Treehaven | WI | 45.49369 | -89.58571 | Restored northern hardwood forest dominated by maple, hemlock, birch, and aspen |
| UKFS | The University of Kansas Field Station | KS | 39.04043 | -95.19215 | Mixed hardwood forest dominated by oak, hickory, and elm |
| UNDE | University of Notre Dame Environmental Research Center | MI | 46.23391 | -89.53725 | Northern hardwood forest dominated by sugar maple |
| WREF | Wind River Experimental Forest | WA | 45.80900 | -121.98231 | Old-growth forest dominated by Douglas-fir, western hemlock, and western red cedar |
| YELL | Yellowstone Northern Range | WY | 44.95348 | -110.53914 | Open pine-dominated forest |

\*Refers to forest type around the tower on which the vertical profile of micrometeorological instruments is mounted, as provided by NEON (Hongyan Luo, personal communication; [site descriptions on NEON website](https://www.neonscience.org/field-sites)).

# Table S2. (Tealeaves parameters)

| variable | vertical position (m) | mean of July daily maximum |
| --- | --- | --- |
| wind speed (m/s) | 10 | 0.24 |
| wind speed (m/s) | 50 | 2.88 |
| relative humidity (%) | 0 | 96.83 |
| relative humidity (%) | 60 | 90.81 |
| air temperature (°C) | 10 | 22.86 |
| air temperature (°C) | 50 | 24.92 |
| PAR | 10 | 203.69 |
| PAR | 60 | 1,738.48 |

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



**Figure S1. Vertical gradients in micrometeorological conditions for all forested sites in the National Ecological Observatory Network (NEON)**. Shown are height profiles in July mean ± 1 standard deviation for maximum photosyntehtically active ratiation (PAR), maximum wind speed, minimum humidity, maximum , and maximum biological temperature, . Site information is given in Supporting Information Table S1, and analysis details in Supporting Information Methods S1.

## References

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

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

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

**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.

**Still CJ, Rastogi B, Page GFM, Griffith DM, Sibley A, Schulze M, Hawkins L, Pau S, Detto M, Helliker BR**. **2021**. Imaging canopy temperature: Shedding (thermal) light on ecosystem processes. *New Phytologist* **230**: 1746–1753.