

1 **Thermal acclimation of stem respiration implies a weaker carbon-climate feedback**

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35 **Abstract:** The efflux of CO₂ from woody stems, a proxy for stem respiration, is a critical carbon flux
36 from ecosystems to atmosphere, increasing with temperature on short timescales. However, plants
37 acclimate their respiratory response to temperature on longer timescales, potentially weakening the
38 carbon-climate feedback. The magnitude of this acclimation is uncertain despite its importance for
39 predicting future climate change. We develop an optimality-based theory dynamically linking stem
40 respiration with leaf water supply to predict its thermal acclimation. We show the theory accurately
41 reproduces observations of spatial and seasonal change. We estimate the global value for current annual
42 stem CO₂ efflux as 27.4±5.9 PgC. By 2100, incorporating thermal acclimation reduces projected stem
43 respiration without considering acclimation by 24% to 46%, thus reducing land ecosystem carbon
44 emissions.

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46 Main text

47 Plant respiration represents about half of the annual carbon flux globally from terrestrial ecosystems
48 to the atmosphere, approximately six times more than anthropogenic carbon emissions (1, 2). The
49 contribution of respiration by stems is not well quantified (3-5), but current models estimate it as around
50 a quarter of total plant respiration (fig. S1). Plants respire their photosynthetic products to support
51 physiological processes and growth (6, 7). As an enzyme-mediated process, respiration increases nearly
52 exponentially with increasing temperature on time frames of minutes to hours (8). Additional respiratory
53 carbon release is thus widely expected in a warming world, leading to more warming (9, 10).

54 In principle, plant respiration is controlled by substrate availability, oxygen supply and the demand
55 for respiratory products. Plants modulate their respiratory response to temperature on timescales of weeks
56 to years due to changes in these driving forces (11-13). This behaviour could weaken the positive feedback
57 between climate warming and carbon emissions from plants. Plants exposed to warmer conditions show
58 a reduced respiration rate at a standardized measurement temperature, and/or a decreased sensitivity to
59 temperature (indicated by a smaller increase in respiratory rate per unit increase in temperature over the
60 short term) compared to plants that have experienced cooler temperatures (11-16). These adjustments are
61 called ‘thermal acclimation’. The more pronounced the thermal acclimation of respiration globally, the
62 weaker the positive feedback between climate warming and carbon emissions.

63 The mechanisms and magnitude of thermal acclimation are still unclear. This is particularly true for
64 stem respiration. Empirical evidence shows that stem respiration scales with nitrogen concentration
65 similarly to leaves and roots, reflecting its enzyme requirements (17, 18). However, the nature of thermal
66 acclimation may differ between tissues. Leaves coordinate their respiratory acclimation with
67 photosynthetic acclimation and have multiple mechanisms for thermal and physiological regulation (14,
68 16, 19). Presumably this is not the case for stems and roots, which likely also have higher thermal inertia
69 than leaves (20). There have been a number of studies on the environmental controls of stem respiration,
70 but no overarching principles have emerged (21-26). The lack of a theoretical basis has precluded any
71 global analysis of the impact of thermal acclimation of stem respiration.

The representation of respiration in Earth System Models (ESMs) is simplistic and largely untested. Many ESMs do not implement time-dependent acclimation of plant respiration rates to warming (27, 28). Models that do consider plant acclimation use empirical approaches and either ignore stem respiration acclimation or assume that stems acclimate in the same way as leaves (29-32), presumably due to the paucity of information about stem respiration. Improved understanding of the magnitude of stem respiration and its acclimation is needed for reliable predictions of the global carbon-climate feedback (33).

Eco-evolutionary optimality (EEO) principles have been shown to provide parameter-sparse predictions of many different plant processes (14, 34-37). EEO hypotheses identify trade-offs between plant resource demand and acquisition that can be expressed mathematically (34). The previous success of EEO in predicting plant eco-physiological processes suggests this approach is also useful to investigate the magnitude of thermal acclimation in stems. Accordingly, this study addresses the following two questions: (1) Is thermal acclimation of stem respiration effectively described by EEO theory? (2) How does thermal acclimation affect the global carbon cycle? We first propose an EEO-based model for the thermal sensitivity of stem respiration, which we test both spatially, using a global dataset, and temporally, using seasonal measurements and a warming experiment. We then apply the resulting model to test the impact of thermal acclimation on the global carbon cycle under future climate.

Theoretical background

Under the assumption that a primary function of sapwood is maintaining the hydraulic continuum as determined by the canopy water demand, we assumed that the cost of doing so – whole-plant stem respiration – is proportional to transpiration from the canopy on a timescale of days to weeks (SI section 2.1). This coupling ensures that total stem respiration, including both maintenance and growth components, is neither more (which would result in non-productive carbon consumption) nor less (which would threaten hydraulic integrity) than that required to support the stem hydraulic continuum. Although long-distance water transport through the xylem is largely driven passively, maintenance of the hydraulic continuum is effectively used here as a proxy for associated energy-requiring processes, including the maintenance of stem water storage capacity and stem water potential, new xylem production, defense and resilience to disturbance (SI section 1.3) (38-42). We combine this hypothesis with physical principles influencing the manner in which respiration and transpiration are coupled and use this relationship to predict the spatial and temporal thermal acclimation of stem respiration. First, we assume that whole-plant stem respiration (R_s , nmol C s⁻¹) is proportional to canopy transpiration (E , nmol H₂O s⁻¹) with a cost factor representing the respiration rate required to maintain a unit of transpiration rate (43). In principle, this cost factor should be influenced by temperature: water has a reduced dynamic viscosity as temperature increases, meaning there is less hydraulic resistance to water transport to the leaves, and thus the cost incurred for supporting a given transpiration rate would be lower. Given that R_s is a product of mass-based respiration rate over time (r_s , nmol C g⁻¹ s⁻¹) and total sapwood mass (M_s , g C), we expect that r_s and M_s also co-vary with E and the respiration cost of transpiration. At a global scale, where spatial variation in both r_s and M_s is large, we assume that r_s and M_s track variation in the cost factor and E , respectively (Eq. 20). Therefore, the thermal response of the cost factor as largely determined by the hydraulic resistance and xylem sap viscosity is the primary control of the variation in r_s along geographic temperature gradients.

For temporal changes at a weekly scale, where the change in M_s is small compared to changes in transpiration, we expect only r_s to be coordinated with temporal variation in both E and the cost factor (Eq. 19). Therefore, the response of r_s to temperature that emerges over time, dominated by acclimation, should be mathematically the same as that emerging across space, dominated by adaptation.

To generate empirically testable predictions for the adjustment of stem respiration to temperature, we calculated r_s at growth temperature ($r_{s,gt}$, $\text{nmol C g}^{-1} \text{ s}^{-1}$) and r_s at a standard temperature of 25°C (r_{s25} , $\text{nmol C g}^{-1} \text{ s}^{-1}$) applying a constant Q_{10} temperature coefficient. $r_{s,gt}$ provides a measure of respiration rate under temperature conditions experienced by plants growing under natural conditions, while r_{s25} allows for a standardized comparison of respiratory capacity (and associated investment in mitochondrial proteins) across sites and species (44). Our model specifically predicts that $r_{s,gt}$ acclimates to increasing temperature by $-2.3\% \text{ K}^{-1}$ (Fig. 1B, Eq. 22), due to the decline in the viscosity of water. A steeper decline, of $-10.1\% \text{ K}^{-1}$, is expected for r_{s25} adjusting to temperature (Fig. 1A, Eq. 20) because of the greater catalytic rates of respiratory enzymes at higher temperatures. The trend in the thermal response when considering acclimation is opposite to the instantaneous response due to enzyme kinetics ($+7.9\% \text{ K}^{-1}$) (Eq. 7), which means that warming in the short term will increase respiration steeply and exponentially. Therefore, with acclimation to warming in the long term, respiration at a given temperature (r_{s25}) is reduced, reflecting reduction in respiratory capacity.

We evaluated the thermal response of stem respiration via empirical analyses using a new Global Stem Respiration Dataset (GSRD) (fig. S2 and tables S1-2) and data from five species measured from a glasshouse warming experiment. GSRD includes data from 187 species sampled at 68 field sites spanning all climate zones (including laboratory measurements from excised branches for 74 species from four sites; plus 8701 measurements made directly on trunks of 114 species from 64 field sites, including 4155 seasonal measurements for three species from one site that were used in our temporal test).

Results

A linear regression of r_{s25} against T_g (mean temperature during the thermal growing season, defined as the period when daily temperatures are above 5°C) showed a strong negative response to higher temperatures across all sites globally: r_{s25} decreased by $9.8 \pm 0.3\% \text{ K}^{-1}$ with warmer temperatures, statistically indistinguishable from our theoretical prediction ($10.1\% \text{ K}^{-1}$) (Fig. 1A, Table 1, table S3). Measurements made in the field and in the laboratory showed a similar thermal response for r_{s25} (field measurements: $-10.1 \pm 0.3\% \text{ K}^{-1}$; laboratory measurements: $-11.0 \pm 3.3\% \text{ K}^{-1}$). Note, the absolute values of the laboratory measurements, $2.97 \pm 1.16 \text{ nmol CO}_2 \text{ g}^{-1} \text{ s}^{-1}$, were generally larger than that of field measurements, $0.87 \pm 0.012 \text{ nmol CO}_2 \text{ g}^{-1} \text{ s}^{-1}$, possibly reflecting differences in the nature of sample material; e.g. smaller branches might have been used for lab measurements and, if so, these might have a higher proportion of living cells (45), or reflecting removal of CO_2 diffusion limitations or CO_2 loss to the transpiration stream when measuring CO_2 efflux on excised tissues under laboratory conditions (Fig. 1A, table S6). Comparisons using site-mean values, to minimize the potential impact of over-representation of individual sites with much larger sample sizes, showed that r_{s25} decreased by $8.1 \pm 1.8\% \text{ K}^{-1}$ with warmer temperatures (fig. S3 and table S4). Calculating r_{s25} from measurements made at temperatures other than 25°C assumed a standard, fixed thermal sensitivity of respiration (see Material & Methods). To minimize

potential effects of that assumption, we also restricted analyses to sites where respiration rate was measured at 25 ± 1 °C; these data showed a similar thermal response in r_{s25} (site-mean: $10.1 \pm 3.8\%$ K⁻¹, all individuals: $15.5 \pm 0.7\%$ K⁻¹) (fig. S4 and table S5). Thus, the observed response of r_{s25} against T_g , considered multiple ways, was in the range of *ca.* -8% K⁻¹ to -15% K⁻¹.

Next we quantified temperature-related trends in $r_{s,gt}$, that is, stem respiration rates estimated under typical thermal growing conditions as opposed to at a standard, set temperature. Again, both observations and theory showed a significant negative response of $r_{s,gt}$ to temperature (data: $-1.5 \pm 0.3\%$ K⁻¹, theory: -2.3% K⁻¹), opposite in trend from that expected from enzyme kinetics alone (Fig. 1B and Table 1).

While the global patterns are consistent with an acclimation response to temperature, they may also reflect species replacement along geographic temperature gradients (fig. S5). However, measurements of seasonal variation from a warming experiment are also consistent with our theoretical predictions. A single boreal site provided continuous data on r_s of three species throughout the growing season. We estimated daily transpiration ($\text{nmol m}^{-2} \text{s}^{-1}$) with an EEO-based Penman-Monteith model accounting for canopy stomatal regulation driven by radiation, temperature, vapor pressure deficit, atmospheric pressure and leaf area index (36). The best predictions of the temporal variation in r_{s25} , indicated by variance inflation factor, root mean square error and R^2 , were given by a 6-day time window for temperature and a 13-day period for transpiration, although alternative periods around one to two weeks generated similar predictions (fig. S6, table S7). Multiple regression showed that r_{s25} declines with acclimated temperature by $10.6 \pm 0.5\%$ K⁻¹ and increases almost proportionally to transpiration ($103.8 \pm 1.8\%$), consistent with the theoretical predictions (temperature: -10.1% K⁻¹, transpiration: 100 %, Fig. 2). When evaluated at the acclimated temperature, $r_{s,gt}$ also showed significant responses to temperature ($-4.7 \pm 0.5\%$ K⁻¹) and to transpiration ($111.7 \pm 1.8\%$), both similar but higher than the theoretical values (temperature: -2.3% K⁻¹, transpiration: 100%) (fig. S7). These small differences between the theoretical and empirical values likely reflect uncertainties in the two predictors or the influence of other potential explanatory variables such as soil moisture (see below). The five species measured in the warming experiment showed a consistent decrease in r_{s25} of $10.6 \pm 1.6\%$ K⁻¹, close to our theoretical prediction of 10.1% (Fig. 3). Individual species show similar trends (Fig. 3 and table S8). The *Pinus* species in this experiment showed a somewhat stronger thermal acclimation response than *Pinus* species in the global analysis ($-8.4 \pm 0.4\%$ K⁻¹), possibly reflecting differences in the temperature range sampled (fig. S5 and table S9).

Based on the agreement between theory and observations, we developed a simple model to estimate the global carbon flux from stem respiration and its contribution to the global carbon cycle (SI section 3.2.1). In this model, total stem respiration rate per unit land area is predicted as the product of sapwood mass and mass-based respiration rate under growth temperature ($r_{s,gt}$), on an annual time-step. Sapwood mass is estimated from total above-ground stem biomass and allometric equations describing the shape of the stem, and sapwood depth (Eq. 35) (46, 47). We simulated $r_{s,gt}$ with a single global parameter (table S10) and T_g to represent the annual thermal growth environment for woody species. The model predicts an annual global carbon release by stem respiration of 27.4 ± 5.9 Pg C in 2010 (Fig. 4A) (48, 49). This is comparable with estimates from most TRENDY models (fig. S8). Modeled stem respiration from forests alone (excluding shrublands and savannas) is 15.3 ± 3.2 Pg C, higher than a previous empirical estimate (25) (6.7 ± 0.5 Pg C) with the difference presumably reflecting different methods of estimation. Global

variation in stem respiration was largely controlled by total stem biomass: regions with higher biomass had higher respiration. The highest stem respiration occurred in tropical forests and in the humid temperate forests of eastern North America, eastern Asia and Europe.

We applied this modelling scheme using different climate change scenarios to assess the influence of thermal acclimation on the carbon flux from stem respiration over the 21st century. The results showed that implementing thermal acclimation led to a reduction in predicted stem respiration of 24% and 46% by 2100 under the weakest (SSP126) and strongest (SSP585) warming scenarios, respectively, and reduced predicted land ecosystem carbon emissions by 10.8 and 24.0 Pg C (Fig. 4B). Some land surface models, including CLM5, CABLE and QUINCY, consider the thermal acclimation of stem respiration but treat it identically to leaf respiration (27, 30, 32, 44). In those models, r_{s25} is predicted to decrease with temperature by 1.83 % K⁻¹, an order of magnitude less than that shown by our empirical analyses. This underestimation of the thermal acclimation of stem respiration led to a higher carbon emission from terrestrial ecosystems, resulting in an overestimation of 4.9 and 11.9 PgC in 2100 under the SSP126 and SSP585 scenarios, respectively (SI section 3.2.5).

Discussion and conclusion

We considered several sources of uncertainty inherent in stem respiration observations from assumptions about mean stem diameter values and the allometric equation for deriving mass-based estimates of respiration from stem surface area-based measurements (SI section 1.1.4). Stem size shows a further significant negative effect on stem respiration (tables S11), probably reflecting size-related variation in the proportion of living cells and likely contributing to the difference between lab and field observations. Uneven geographic coverage of observations, with relatively few sites from the tropics and southern hemisphere, may have introduced further biases. Nevertheless, the trends are consistent across the range of temperatures, including boreal and tropical sites. A remaining uncertainty concerns the use of stem CO₂ efflux as a proxy for stem respiration, since there can be other processes affecting stem CO₂ efflux such as CO₂ refixation in bark and dissolution of CO₂ in xylem sap (50-52). Nevertheless, the congruence of the results across different sources and subsets of the data (Figs. 1-3, figs. S3-5, 7, 9-10, Table 1 and tables S3-5, 7-9, 12) and the similarity between the observed and predicted relationships suggests that our conclusions about the thermal response of stem respiration are robust. Data limitations preclude further analysis of the sensitivity of respiration to other environmental factors, such as soil moisture (24, 53) or CO₂ concentration. However, we note that vapor pressure deficit had a positive influence on r_{s25} , in line with our theoretical prediction (SI section 2.2, figs. S11-12 and table S13). Short-term thermal sensitivity (i.e., Q_{10} temperature coefficient) might itself also acclimate to warming and modify the estimates of r_{s25} and $r_{s,gt}$ (9). However, our sensitivity analyses applying a range of Q_{10} values (table S14) and without temperature standardization (fig. S4 and table S5) show that variation in Q_{10} has minor influence on the agreement between the theoretical prediction and empirical observations. Overall, stem respiration – as our hypothesis predicts – appears to show a much stronger thermal acclimation than leaf respiration, which shows a weak but positive response to warming (16). This disparity potentially reflects their different driving processes and thermal conditions. In particular, leaf respiration tracks the maximum capacity of carboxylation, phloem-loading of photosynthates and turnover of photosynthetic proteins (6, 14, 16). Acclimated carboxylation capacity increases with temperature, compensating for

enhanced photorespiration under warmer condition, implying a positive thermal response in leaf respiratory acclimation (16). This is probably not the case for woody tissues. Furthermore, leaves are more likely to be sun-exposed and do not have the insulating properties of bark tissue (20, 54). Experimental studies will be needed to reveal the mechanisms controlling the acclimation of stem and leaf respiration.

We have demonstrated that the application of EEO principles provides a simple way to predict stem respiration and its thermal acclimation, consistent with empirical evidence. This approach could and should be implemented in ESMs. The acclimation response to growth temperature in stem respiration is much stronger than that in leaf respiration. This suggests a potential for enhanced carbon use efficiency in a warming world, a subject still hotly debated (55-57). Enhanced carbon use efficiency would, in turn, substantially weaken the expected positive climate-carbon feedback, enhancing the degree to which ecosystems globally slow the rate of climate change.

References and Notes

1. P. Ciais *et al.*, in *Climate Change 2013: The Physical Science Basis*. (Cambridge University Press, 2014), pp. 465-570.
2. P. Friedlingstein *et al.*, Global Carbon Budget 2023. *Earth Syst Sci Data* **15**, 5301-5369 (2023).
3. M. Campioli *et al.*, Evaluating the convergence between eddy-covariance and biometric methods for assessing carbon budgets of forests. *Nat Commun* **7**, 1-12 (2016).
4. D.-X. Guan *et al.*, CO₂ fluxes over an old, temperate mixed forest in northeastern China. *Agricultural and Forest Meteorology* **137**, 138-149 (2006).
5. Y. Malhi *et al.*, Comprehensive assessment of carbon productivity, allocation and storage in three Amazonian forests. *Global Change Biology* **15**, 1255-1274 (2009).
6. J. S. Amthor, The McCree-de Wit-Penning de Vries-Thornley respiration paradigms: 30 years later. *Annals of Botany* **86**, 1-20 (2000).
7. F. d. Vries, The cost of maintenance processes in plant cells. *Annals of Botany* **39**, 77-92 (1975).
8. M. A. Hessel *et al.*, Convergence in the temperature response of leaf respiration across biomes and plant functional types. *P Natl Acad Sci USA* **113**, 3832-3837 (2016).
9. P. M. Cox, R. A. Betts, C. D. Jones, S. A. Spall, I. J. Totterdell, Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* **408**, 184-187 (2000).
10. C. Huntingford *et al.*, Simulated resilience of tropical rainforests to CO₂-induced climate change. *Nat Geosci* **6**, 268-273 (2013).
11. O. K. Atkin, M. G. Tjoelker, Thermal acclimation and the dynamic response of plant respiration to temperature. *Trends Plant Sci* **8**, 343-351 (2003).
12. K. Y. Crous, J. Uddling, M. G. De Kauwe, Temperature responses of photosynthesis and respiration in evergreen trees from boreal to tropical latitudes. *New Phytologist* **234**, 353-374 (2022).
13. P. B. Reich *et al.*, Boreal and temperate trees show strong acclimation of respiration to warming. *Nature* **531**, 633-+ (2016).
14. Y. H. Ren *et al.*, Reduced global plant respiration due to the acclimation of leaf dark respiration coupled with photosynthesis. *New Phytologist* **241**, 578-591 (2024).
15. N. G. Smith, G. Y. Li, J. S. Dukes, Short-term thermal acclimation of dark respiration is greater in non-photosynthetic

than in photosynthetic tissues. *Aob Plants* **11**, plz064 (2019).

16. H. Wang *et al.*, Acclimation of leaf respiration consistent with optimal photosynthetic capacity. *Global Change Biology* **26**, 2573-2583 (2020).

17. P. B. Reich *et al.*, Scaling of respiration to nitrogen in leaves, stems and roots of higher land plants. *Ecol Lett* **11**, 793-801 (2008).

18. A. C. Westerband *et al.*, Nitrogen concentration and physical properties are key drivers of woody tissue respiration. *Annals of Botany* **129**, 633-646 (2022).

19. B. C. Posch *et al.*, Intensive leaf cooling promotes tree survival during a record heatwave. *P Natl Acad Sci USA* **121**, (2024).

20. Q. Yang, Ming Xu, Yonggang Chi and Yunpu Zheng., Relationship between stem CO₂ efflux and stem temperature at different measuring depths in *Pinus massoniana* trees. *Acta Ecologica Sinica* **36**, 229-235 (2016).

21. J. Q. Chambers *et al.*, Respiration from a tropical forest ecosystem: Partitioning of sources and low carbon use efficiency. *Ecol Appl* **14**, 72-88 (2004).

22. D. Gansert, K. Backes, T. Ozaki, Y. Kakubari, Seasonal variation of branch respiration of a treeline forming (*Betula ermanii* Cham.) and a montane (*Fagus crenata* Blume) deciduous broad-leaved tree species on Mt. Fuji, Japan. *Flora* **197**, 186-202 (2002).

23. M. B. Lavigne, M. G. Ryan, Growth and maintenance respiration rates of aspen, black spruce and jack pine stems at northern and southern BOREAS sites. *Tree Physiology* **17**, 543-551 (1997).

24. L. Rowland *et al.*, Drought stress and tree size determine stem CO₂ efflux in a tropical forest. *New Phytologist* **218**, 1393-1405 (2018).

25. J. Y. Yang, Y. J. He, D. P. Aubrey, Q. L. Zhuang, R. O. Teskey, Global patterns and predictors of stem CO₂ efflux in forest ecosystems. *Global Change Biology* **22**, 1433-1444 (2016).

26. A. Zach, V. Horna, C. Leuschner, Diverging temperature response of tree stem CO₂ release under dry and wet season conditions in a tropical montane moist forest. *Trees-Structure and Function* **24**, 285-296 (2010).

27. G. Krinner *et al.*, A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system. *Global Biogeochem Cy* **19**, GB1015 (2005).

28. G. Y. Niu *et al.*, The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements. *Journal of Geophysical Research-Atmospheres* **116**, D12109 (2011).

29. D. B. Clark *et al.*, The Joint UK Land Environment Simulator (JULES), model description - Part 2: Carbon fluxes and vegetation dynamics. *Geosci Model Dev* **4**, 701-722 (2011).

30. V. Haverd *et al.*, A new version of the CABLE land surface model (Subversion revision r4601) incorporating land use and land cover change, woody vegetation demography, and a novel optimisation-based approach to plant coordination of photosynthesis. *Geosci Model Dev* **11**, 2995-3026 (2018).

31. D. M. Lawrence *et al.*, The Community Land Model Version 5: Description of New Features, Benchmarking, and Impact of Forcing Uncertainty. *J Adv Model Earth Sy* **11**, 4245-4287 (2019).

32. T. Thum *et al.*, A new model of the coupled carbon, nitrogen, and phosphorus cycles in the terrestrial biosphere (QUINCY v1.0; revision 1996). *Geosci Model Dev* **12**, 4781-4802 (2019).

33. D. L. Lombardozzi, G. B. Bonan, N. G. Smith, J. S. Dukes, R. A. Fisher, Temperature acclimation of photosynthesis and respiration: A key uncertainty in the carbon cycle-climate feedback. *Geophysical Research Letters* **42**, 8624-8631 (2015).

311 34. S. P. Harrison *et al.*, Eco-evolutionary optimality as a means to improve vegetation and land-surface models. *New*
312 *Phytologist* **231**, 2125-2141 (2021).

313 35. B. D. Stocker *et al.*, Empirical evidence and theoretical understanding of ecosystem carbon and nitrogen cycle
314 interactions. *New Phytologist* **245**, 49-68 (2025).

315 36. S. Tan *et al.*, Towards a universal evapotranspiration model based on optimality principles. *Agricultural and Forest*
316 *Meteorology* **336**, 109478 (2023).

317 37. H. Wang *et al.*, Towards a universal model for carbon dioxide uptake by plants. *Nat Plants* **3**, 734-741 (2017).

318 38. A. Gauthey *et al.*, Mechanisms of xylem hydraulic recovery after drought in *Eucalyptus saligna*. *Plant Cell and*
319 *Environment* **45**, 1216-1228 (2022).

320 39. S. Martorell, A. Diaz-Espejo, H. Medrano, M. C. Ball, B. Choat, Rapid hydraulic recovery in *Eucalyptus pauciflora* after
321 drought: linkages between stem hydraulics and leaf gas exchange. *Plant Cell and Environment* **37**, 617-626 (2014).

322 40. H. Morris *et al.*, A global analysis of parenchyma tissue fractions in secondary xylem of seed plants. *New Phytologist*
323 **209**, 1553-1565 (2016).

324 41. M. Tomasella, E. Petrusa, F. Petruzzellis, A. Nardini, V. Casolo, The Possible Role of Non-Structural Carbohydrates in
325 the Regulation of Tree Hydraulics. *Int J Mol Sci* **21**, 144 (2020).

326 42. M. J. B. Zeppel *et al.*, Embolism recovery strategies and nocturnal water loss across species influenced by
327 biogeographic origin. *Ecol Evol* **9**, 5348-5361 (2019).

328 43. I. C. Prentice, N. Dong, S. M. Gleason, V. Maire, I. J. Wright, Balancing the costs of carbon gain and water transport:
329 testing a new theoretical framework for plant functional ecology. *Ecol Lett* **17**, 82-91 (2014).

330 44. O. K. Atkin *et al.*, Global variability in leaf respiration in relation to climate, plant functional types and leaf traits. *New*
331 *Phytologist* **206**, 614-636 (2015).

332 45. M. A. Cavaleri, S. F. Oberbauer, M. G. Ryan, Wood CO₂ efflux in a primary tropical rain forest. *Global Change Biology*
333 **12**, 2442-2458 (2006).

334 46. M. Santoro *et al.*, The global forest above-ground biomass pool for 2010 estimated from high-resolution satellite
335 observations. *Earth Syst Sci Data* **13**, 3927-3950 (2021).

336 47. M. Thurner *et al.*, Sapwood biomass carbon in northern boreal and temperate forests. *Global Ecol Biogeogr* **28**, 640-
337 660 (2019).

338 48. C. Huntingford *et al.*, Implications of improved representations of plant respiration in a changing climate. *Nat*
339 *Commun* **8**, 1602 (2017).

340 49. M. Jung *et al.*, Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived
341 from eddy covariance, satellite, and meteorological observations. *Journal of Geophysical Research-Biogeosciences*
342 **116**, G00J07 (2011).

343 50. R. L. Salomón, L. De Roo, J. Oleksyn, D. J. W. De Pauw, K. Steppe, TReSpire - a biophysical TRee Stem respiration model.
344 *New Phytologist* **225**, 2214-2230 (2020).

345 51. R. L. Salomón *et al.*, The quandary of sources and sinks of CO₂ efflux in tree stems-new insights and future directions.
346 *Tree Physiology* **44**, tpad157 (2024).

347 52. R. O. Teskey, A. Saveyn, K. Steppe, M. A. McGuire, Origin, fate and significance of CO₂ in tree stems. *New Phytologist*
348 **177**, 17-32 (2008).

349 53. C. W. Huang *et al.*, The effect of plant water storage on water fluxes within the coupled soil-plant system. *New*
350 *Phytologist* **213**, 1093-1106 (2017).

351 54. N. L. Harris, C. A. S. Hall, A. E. Lugo, Estimates of species- and ecosystem-level respiration of woody stems along an

elevational gradient in the Luquillo Mountains, Puerto Rico. *Ecol Model* **216**, 253-264 (2008).

55. M. Campioli, Vicca, S., Luyssaert, S. et al., Biomass production efficiency controlled by management in temperate and boreal ecosystems. *Nat Geosci* **8**, 843–846 (2015).

56. A. Collalti et al., Forest production efficiency increases with growth temperature. *Nat Commun* **11**, 5322 (2020).

57. S. Manzoni et al., Reviews and syntheses: Carbon use efficiency from organisms to ecosystems - definitions, theories, and empirical evidence. *Biogeosciences* **15**, 5929-5949 (2018).

58. H. Zhang et al., Global Stem Respiration Dataset (GSRD), version 1, Science Data Bank (2024); <https://doi.org/10.57760/sciencedb.ecodb.00170>

59. J. Kattge et al., TRY plant trait database - enhanced coverage and open access. *Global Change Biology* **26**, 119-188 (2020).

60. M. L. Pruyn, B. L. Gartner, M. E. Harmon, Within-stem variation of respiration in (Douglas-fir) trees. *New Phytologist* **154**, 359-372 (2002).

61. R. Spicer, in *Vascular transport in plants*, M. Z. N Holbrook, Ed. (Elsevier Academic Press, Burlington, MA, USA, 2005), pp. 457–475.

62. R. Spicer, N. M. Holbrook, Parenchyma cell respiration and survival in secondary xylem: does metabolic activity decline with cell age? *Plant Cell and Environment* **30**, 934-943 (2007).

63. F. C. Meinzer, G. Goldstein, J. L. Andrade, Regulation of water flux through tropical forest canopy trees: Do universal rules apply? *Tree Physiology* **21**, 19-26 (2001).

64. J. Rodríguez-Calcerrada et al., Stem CO₂ efflux in six co-occurring tree species: underlying factors and ecological implications. *Plant Cell and Environment* **38**, 1104-1115 (2015).

65. D. S. Falster et al., BAAD: a Biomass And Allometry Database for woody plants. *Ecology* **96**, 1445-1445 (2015).

66. L. Plavcová, G. Hoch, H. Morris, S. Ghiasi, S. Jansen, The amount of parenchyma and living fibers affects storage of nonstructural carbohydrates in young stems and roots of temperate trees. *American Journal of Botany* **103**, 603-612 (2016).

67. M. Acosta, M. Pavelka, R. Pokorný, D. Janous, M. V. Marek, Seasonal variation in CO₂ efflux of stems and branches of Norway spruce trees. *Annals of Botany* **101**, 469-477 (2008).

68. O. K. Atkin, D. Bruhn, G. M. Tjoelker, in *Plant Respiration: From Cell to Ecosystem*, H. Lambers, M. Ribas-Carbo, Eds. (Springer Dordrecht, 2005), pp. 95-135.

69. E. Darenova, P. Horáček, J. Krejza, R. Pokorný, M. Pavelka, Seasonally varying relationship between stem respiration, increment and carbon allocation of Norway spruce trees. *Tree Physiology* **40**, 943-955 (2020).

70. E. Darenova, J. Szatniewska, M. Acosta, M. Pavelka, Variability of stem CO₂ efflux response to temperature over the diel period. *Tree Physiology* **39**, 877-887 (2019).

71. M. G. Ryan, R. M. Hubbard, D. A. Clark, R. L. Sanford, Woody-Tissue Respiration for Simarouba-Amara and Minquartia-Guianensis, 2 Tropical Wet Forest Trees with Different Growth Habits. *Oecologia* **100**, 213-220 (1994).

72. S. T. Gower et al., Carbon distribution and aboveground net primary production in aspen, jack pine, and black spruce stands in Saskatchewan and Manitoba, Canada. *Journal of Geophysical Research-Atmospheres* **102**, 29029-29041 (1997).

73. J. L. Monteith, Evaporation and environment. *Symposia of the Society for Experimental Biology* **19**, 205-234 (1965).

74. S. Tan, H. Wang, I. C. Prentice, K. Yang, Land-surface evapotranspiration derived from a first-principles primary production model. *Environmental Research Letters* **16**, 104047 (2021).

75. M. Cucchi et al., WFDE5: bias-adjusted ERA5 reanalysis data for impact studies. *Earth Syst Sci Data* **12**, 2097-2120

(2020).

76. Z. C. Zhu *et al.*, Global Data Sets of Vegetation Leaf Area Index (LAI)3g and Fraction of Photosynthetically Active Radiation (FPAR)3g Derived from Global Inventory Modeling and Mapping Studies (GIMMS) Normalized Difference Vegetation Index (NDVI3g) for the Period 1981 to 2011. *Remote Sens-Basel* **5**, 927-948 (2013).

77. J. Chave *et al.*, Towards a worldwide wood economics spectrum. *Ecol Lett* **12**, 351-366 (2009).

78. African Wood Density Database, World Agroforestry Centre, Nairobi (2012);
<https://apps.worldagroforestry.org/treesnmarkets/wood/index.php#>

79. G. Hoch, A. Richter, C. Körner, Non-structural carbon compounds in temperate forest trees. *Plant Cell and Environment* **26**, 1067-1081 (2003).

80. M. J. O'Brien, S. Leuzinger, C. D. Philipson, J. Tay, A. Hector, Drought survival of tropical tree seedlings enhanced by non-structural carbohydrate levels. *Nat Clim Change* **4**, 710-714 (2014).

81. J. S. Plavcová L, The role of xylem parenchyma in the storage and utilization of non-structural carbohydrates. *Functional and ecological xylem anatomy*, 209–234 (2015).

82. S. Salleo, M. A. Lo Gullo, P. Trifilò, A. Nardini, New evidence for a role of vessel-associated cells and phloem in the rapid xylem refilling of cavitated stems of *Laurus nobilis* L. *Plant Cell and Environment* **27**, 1065-1076 (2004).

83. A. R. Biggs, Occurrence and Location of Suberin in Wound Reaction Zones in Xylem of 17 Tree Species. *Phytopathology* **77**, 718-725 (1987).

84. G. Deflorio, C. Johnson, S. Fink, F. W. M. R. Schwarze, Decay development in living sapwood of coniferous and deciduous trees inoculated with six wood decay fungi. *Forest Ecology and Management* **255**, 2373-2383 (2008).

85. U. Schmitt, W. Liese, Response of Xylem Parenchyma by Suberization in Some Hardwoods after Mechanical Injury. *Trees-Structure and Function* **8**, 23-30 (1993).

86. A. L. Shigo, Compartmentalization — a Conceptual-Framework for Understanding How Trees Grow and Defend Themselves. *Annu Rev Phytopathol* **22**, 189-214 (1984).

87. R. Borchert, W. T. Pockman, Water storage capacitance and xylem tension in isolated branches of temperate and tropical trees. *Tree Physiology* **25**, 457-466 (2005).

88. N. M. Holbrook, in *Stems and trunks in plant form and function*, B. Gartner, Ed. (Academic Press, 1995), pp. 151–174.

89. M. Nawrot, W. Pazdrowski, M. Szymański, Dynamics of heart-wood formation and axial and radial distribution of sapwood and heartwood in stems of European larch (*Larix decidua* Mill.). *Journal of Forest Science*, 409–417 (2008).

90. I. Pinto, H. Pereira, A. Usenius, Heartwood and sapwood development within maritime pine (*Pinus pinaster* Ait.) stems. *Trees-Structure and Function* **18**, 284-294 (2004).

91. I. Burgert, A. Bernasconi, D. Eckstein, Evidence for the strength function of rays in living trees. *Holz Roh Werkst* **57**, 397-399 (1999).

92. I. Burgert, D. Eckstein, The tensile strength of isolated wood rays of beech (*Fagus sylvatica* L.) and its significance for the biomechanics of living trees. *Trees-Structure and Function* **15**, 168-170 (2001).

93. A. Reiterer, I. Burgert, G. Sinn, S. Tschegg, The radial reinforcement of the wood structure and its implication on mechanical and fracture mechanical properties - A comparison between two tree species. *J Mater Sci* **37**, 935-940 (2002).

94. M. A. Brodersen CR, Choat B, Matthews M, Shackel K, Dynamics of embolism repair in grapevine: in vivo visualisations using HRCT. *Plant Physiology*, 1088–1095 (2010).

95. G. G. Clearwater MJ, in *Vascular transport in plants*, M. Z. NM Holbrook, Ed. (Elsevier Academic Press, 2005), pp. 375–399.

434 96. S. Salleo, P. Trifilò, S. Esposito, A. Nardini, M. A. Lo Gullo, Starch-to-sugar conversion in wood parenchyma of field-
435 growing plants: a component of the signal pathway for embolism repair? *Funct Plant Biol* **36**, 815-825 (2009).

436 97. S. Jansen *et al.*, Do quantitative vessel and pit characters account for ion-mediated changes in the hydraulic
437 conductance of angiosperm xylem? *New Phytologist* **189**, 218-228 (2011).

438 98. A. Nardini, S. Salleo, S. Jansen, More than just a vulnerable pipeline: xylem physiology in the light of ion-mediated
439 regulation of plant water transport. *Journal of Experimental Botany* **62**, 4701-4718 (2011).

440 99. M. Santiago, V. Pagay, A. D. Stroock, Impact of Electroviscosity on the Hydraulic Conductance of the Bordered Pit
441 Membrane: A Theoretical Investigation. *Plant Physiology* **163**, 999-1011 (2013).

442 100. M. A. Zwieniecki, P. J. Melcher, N. M. Holbrook, Hydrogel control of xylem hydraulic resistance in plants. *Science* **291**,
443 1059-1062 (2001).

444 101. D. J. Hearn, T. Poulsen, R. Spicer, The Evolution of Growth Forms with Expanded Root and Shoot Parenchymatous
445 Storage Is Correlated across the Eudicots. *Int J Plant Sci* **174**, 1049-1061 (2013).

446 102. S. Pfautsch, J. Renard, M. G. Tjoelker, A. Salih, Phloem as Capacitor: Radial Transfer of Water into Xylem of Tree Stems
447 Occurs via Symplastic Transport in Ray Parenchyma. *Plant Physiology* **167**, 963-+ (2015).

448 103. A. J. E. Vanbel, Xylem-Phloem Exchange Via the Rays - the Undervalued Route of Transport. *Journal of Experimental*
449 *Botany* **41**, 631-644 (1990).

450 104. H. Yuan, Y. J. Dai, Z. Q. Xiao, D. Y. Ji, W. Shangguan, Reprocessing the MODIS Leaf Area Index products for land surface
451 and climate modelling. *Remote Sens Environ* **115**, 1171-1187 (2011).

452 105. I. Harris, T. J. Osborn, P. Jones, D. Lister, Version 4 of the CRU TS monthly high-resolution gridded multivariate climate
453 dataset. *Sci Data* **7**, 109 (2020).

454 106. S. P. Harrison *et al.*, Ecophysiological and bioclimatic foundations for a global plant functional classification. *J Veg Sci*
455 **21**, 300-317 (2010).

456 107. I. C. Prentice *et al.*, A Global Biome Model Based on Plant Physiology and Dominance, Soil Properties and Climate. *J*
457 *Biogeogr* **19**, 117-134 (1992).

458 108. I. C. Prentice, M. T. Sykes, W. Cramer, A Simulation-Model for the Transient Effects of Climate Change on Forest
459 Landscapes. *Ecol Model* **65**, 51-70 (1993).

460 109. P. Kauppi, M. Posch, Sensitivity of Boreal Forests to Possible Climatic Warming. *Climatic Change* **7**, 45-54 (1985).

461 110. S. Tuhkanen, Climatic parameters and indices in plant geography. *Acta phytogeog* **16**, 1-105 (1980).

462 111. T. W. Davis *et al.*, Simple process-led algorithms for simulating habitats (SPLASH v.1.0): robust indices of radiation,
463 evapotranspiration and plant-available moisture. *Geosci Model Dev* **10**, 689-708 (2017).

464 112. M. New, D. Lister, M. Hulme, I. Makin, A high-resolution data set of surface climate over global land areas. *Climate*
465 *Res* **21**, 1-25 (2002).

466 113. O. Boucher *et al.*, IPSL IPSL-CM6A-LR model output prepared for CMIP6 ScenarioMIP ssp585, Earth System Grid
467 Federation (2019);
468 <https://doi.org/10.22033/ESGF/CMIP6.5271>

469 114. O. Boucher *et al.*, IPSL IPSL-CM6A-LR model output prepared for CMIP6 ScenarioMIP ssp126, Earth System Grid
470 Federation (2019);
471 <https://doi.org/10.22033/ESGF/CMIP6.5262>

472 115. G. Danabasoglu, NCAR CESM2 model output prepared for CMIP6 ScenarioMIP ssp126, Earth System Grid Federation
473 (2019);
474 <https://doi.org/10.22033/ESGF/CMIP6.7746>

475 116. G. Danabasoglu, NCAR CESM2 model output prepared for CMIP6 ScenarioMIP ssp585, Earth System Grid Federation
476 (2019);
477 <https://doi.org/10.22033/ESGF/CMIP6.7768>

478 117. S. Shim *et al.*, NIMS-KMA UKESM1.0-LL model output prepared for CMIP6 ScenarioMIP ssp585, Earth System Grid
479 Federation (2021);
480 <https://doi.org/10.22033/ESGF/CMIP6.8457>

481 118. S. Shim *et al.*, NIMS-KMA UKESM1.0-LL model output prepared for CMIP6 ScenarioMIP ssp126, Earth System Grid
482 Federation (2021);
483 <https://doi.org/10.22033/ESGF/CMIP6.8433>

484 119. T. Ziehn *et al.*, CSIRO ACCESS-ESM1.5 model output prepared for CMIP6 ScenarioMIP ssp126, Earth System Grid
485 Federation (2019);
486 <https://doi.org/10.22033/ESGF/CMIP6.4320>

487 120. T. Ziehn *et al.*, CSIRO ACCESS-ESM1.5 model output prepared for CMIP6 ScenarioMIP ssp585, Earth System Grid
488 Federation (2019);
489 <https://doi.org/10.22033/ESGF/CMIP6.4333>

490 121. S. Sitch *et al.*, Trends and Drivers of Terrestrial Sources and Sinks of Carbon Dioxide: An Overview of the TRENDY
491 Project. *Global Biogeochem Cy* **38**, e2024GB008102 (2024).

492 122. L. M. Silva *et al.*, The potential link between gas diffusion and embolism spread in angiosperm xylem: Evidence from
493 flow-centrifuge experiments and modelling. *Plant Cell and Environment*, 4977-4991 (2024).

494 123. J. R. Schramski, A. I. Dell, J. M. Grady, R. M. Sibily, J. H. Brown, Metabolic theory predicts whole-ecosystem properties.
495 *P Natl Acad Sci USA* **112**, 2617-2622 (2015).

496 124. P. G. Jarvis, in *Plant photosynthetic production. Manual of methods.*, W. N. Junk, Ed. (The Hague, 1971), pp. 566-631.

497 125. B. D. Stocker *et al.*, P-model v1.0: an optimality -based light use efficiency model for simulating ecosystem gross
498 primary production. *Geosci Model Dev* **13**, 1545-1581 (2020).

499 126. J. Fox, S. Weisberg, An R Companion to Applied Regression, 3, (2019);
500 <https://socialsciences.mcmaster.ca/jfox/Books/Companion/>

501 127. J. R. Lockwood, D. F. McCaffrey, Correcting for Test Score Measurement Error in ANCOVA Models for Estimating
502 Treatment Effects. *J Educ Behav Stat* **39**, 22-52 (2014).

503 128. J. R. Lockwood, D. F. McCaffrey, Simulation-Extrapolation with Latent Heteroskedastic Error Variance. *Psychometrika*
504 **82**, 717-736 (2017).

505 129. S. Rabe-Hesketh, A. Pickles, A. Skrondal, Correcting for covariate measurement error in logistic regression using
506 nonparametric maximum likelihood estimation. *Stat Model* **3**, 215-232 (2003).

507 130. M. M. Douglas Bates, Ben Bolker, Steve Walker, Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical*
508 *Software*. **67**, 1-48 (2019).

509 131. K. Bartoń, MuMIn: Multi-Model Inference, R package version (2024);
510 <https://CRAN.R-project.org/package=MuMIn>

511 132. P. Breheny, W. Burchett, Visualization of Regression Models Using visreg. *R J* **9**, 56-71 (2017).

512 133. H. Wickham *et al.*, ggplot2: Elegant Graphics for Data Analysis, (2009);
513 <https://ggplot2.tidyverse.org>

514 134. M. Van Oijen, A. Schapendonk, M. Höglind, On the relative magnitudes of photosynthesis, respiration, growth and
515 carbon storage in vegetation. *Annals of Botany* **105**, 793-797 (2010).

516

517 **Acknowledgments:** We thank Mark E. Olson and Christian Körner for comments on the preprint of this
518 paper and acknowledge Allyson Eller for her contribution to data collection in Australia. We thank the
519 editor and reviewers for valuable comments and suggestions.

520 **Funding:** This project is supported by

521 National Natural Science Foundation of China 42361144875 (HW)

522 National Key Research and Development Program of China 2023YFF1305500 (HW)

523 Hainan Institute of National Park Research Program KY-23ZK01 (HW)

524 Tsinghua University Initiative Scientific Research Program 20223080041 (HW)

525 Schmidt Sciences (HW, ICP, SPH, NGS, TK)

526 Australian Research Council DP170103410 (ICP, IJW)

527 Australian Research Council DP220102547 (IJW, HW)

528 Australian Research Council CE200100015 (IJW)

529 the United States National Science Foundation DEB-2045968 (NGS)

530 the United States National Science Foundation DBI-2021898 (PBR)

531 the RUBISCO SFA, sponsored by the Regional and Global Model Analysis Program in the U.S.
532 Department of Energy (DOE) Office of Science (T.F.K.)

533 DOE Early Career Research award (DE-SC0021023) (T.F.K.)

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536 Data: H.Z., I.J.W., A.C.W., N.S., P.R., L.R., H.M., L.P. and S.J.

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538 Visualization: H.Z. and N.B.N.

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540 Writing, review and editing: all.

541 **Competing interests:** Authors declare that they have no competing interests.

542 **Data and materials availability:** Data used in this study and original R code (version 4.0.2) used to
543 analyze results have been deposited as a public archived databases (58) or in the Supplementary
544 Materials.

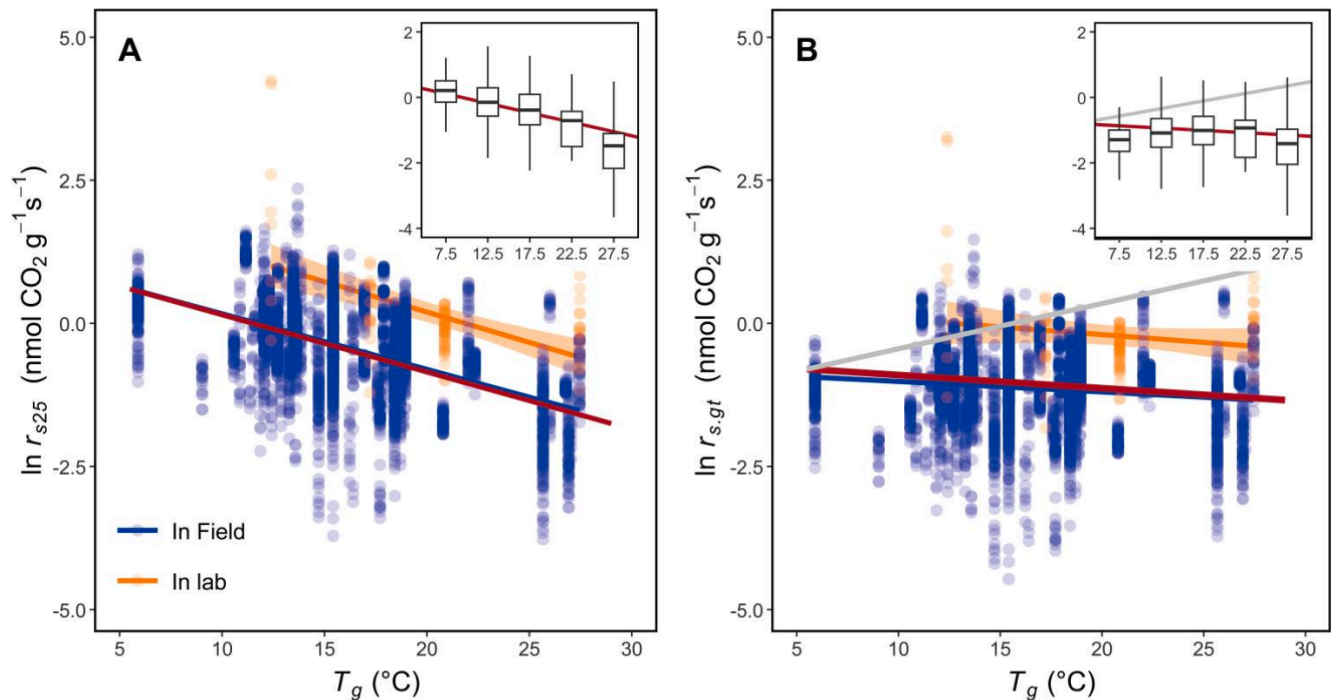
545 **Supplementary Materials**

546 Materials and Methods

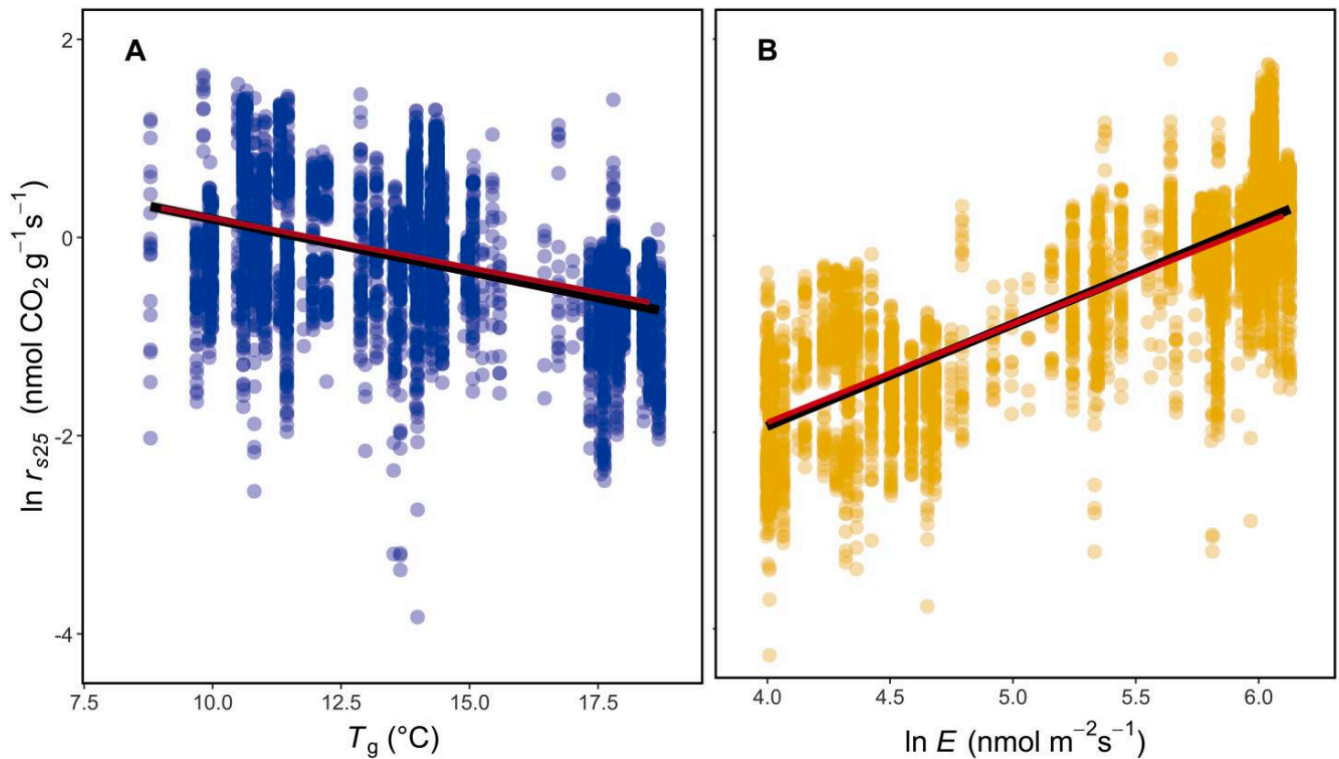
547 Figures S1 to S12

548	Tables S1 to S14
549	References 59-132

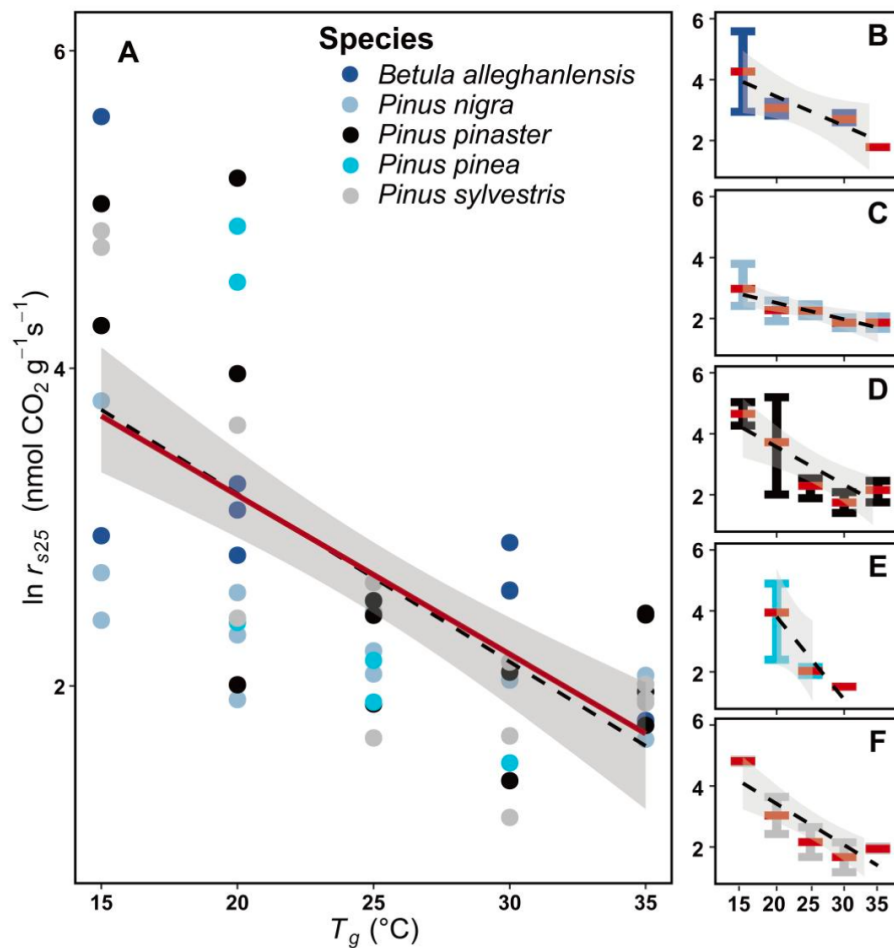
550 **Figure 1. Global trends of stem respiration at reference temperature (r_{s25}) and at growth**
 551 **temperature ($r_{s,gt}$) in relation to growth temperature (the mean temperature during the thermal**
 552 **growing season when daily temperature above 5°C, T_g). (A)** Stem respiration was measured in the
 553 laboratory (orange dots) and in the field (blue dots). r_{s25} represents stem respiration standardized to the
 554 reference temperature of 25°C. Solid fitted lines are shown for the laboratory data (orange line), field data
 555 (blue line) separately (Mathematical details are provided in Table 1). The shaded area represents the 95%
 556 confidence intervals. The solid red line is the theoretical prediction of thermal sensitivity, whose slope is
 557 $-10.1\% \text{ K}^{-1}$. The inset figure presents an overview of all the main figure data aggregated into temperature
 558 bins. Horizontal and vertical coordinates are the same as that in the main figure. **(B)** $r_{s,gt}$ represents stem
 559 respiration standardized to growth temperature, using the same color coding as in (A). The solid red line
 560 is the theoretical prediction of thermal sensitivity of $r_{s,gt}$, whose slope is $-2.3\% \text{ K}^{-1}$. The instantaneous
 561 thermal response is also shown, based on a fixed- Q_{10} function (gray line).



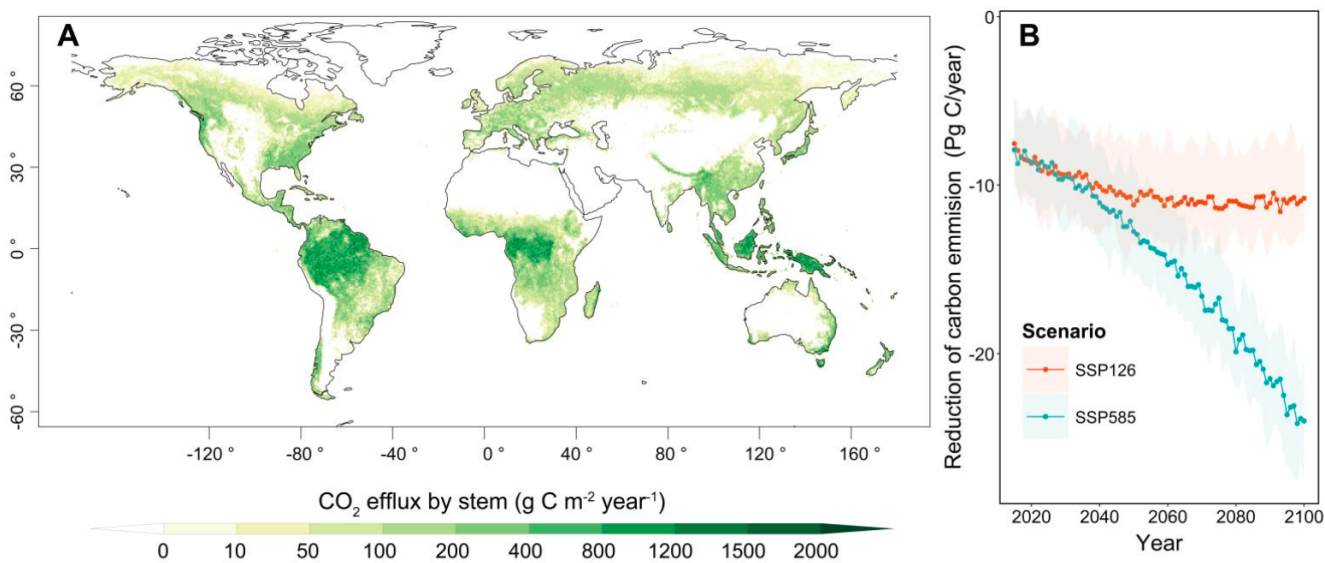
563 **Figure 2. Partial residual plots showing the relationship between stem respiration and temperature**
 564 **and transpiration when other factors are held constant. (A)** Growth temperature (T_g) is an average of
 565 the six days before stem respiration was measured. r_{s25} is stem respiration, natural-log transformed, at the
 566 reference temperature of 25°C. **(B)** Transpiration (E) is an average of the thirteen days before measurement
 567 and was natural-log transformed. The solid black line is the relationship fitted via multiple regression
 568 ($\ln r_{s25} = (-0.106 \pm 0.005) \times T_g + (1.04 \pm 0.018) \times \ln E$, $R^2=0.49$, $VIF=2.01$, $p<0.001$). The red solid line is
 569 the theoretical prediction, with a coefficient of $-10.1\% \text{ K}^{-1}$ and $100\% (\text{nmol H}_2\text{O m}^{-2} \text{ s}^{-1})^{-1}$ for temperature
 570 and $\ln$ transpiration, respectively.



572 **Figure 3. Relationship between stem respiration and growing temperature derived from a warming**
 573 **experiment.** The warming experiment was conducted using five species: *Betula alleghaniensis*, *Pinus*
 574 *nigra*, *Pinus pinaster*, *Pinus pinea* and *Pinus sylvestris*. **(A)** r_{s25} is stem respiration, natural-log
 575 transformed, at the reference temperature of 25°C. Growth temperature (T_g) is the temperature at which
 576 individual species were grown. Different colored points represent different species. The dashed line was
 577 fitted ($\ln r_{s25} = (0.106 \pm 0.007) \times T_g$, $R^2 = 0.44$) using linear regression analysis on all the data. The red
 578 solid line is the theoretical prediction, with a coefficient of $-10.1\%K^{-1}$. **(B-F)** Box plots representing
 579 different species, with colors consistent with those in (A). The short horizontal line represents the
 580 maximum and minimum values, while the red short horizontal line represents the average value under
 581 each T_g . The dashed line is the fitted line with shaded area representing the 95% confidence intervals.
 582 Mathematical details are provided in table S8.



584 **Figure 4. Predicted global stem respiration under present conditions and in response to future**
585 **warming. (A)** Stem respiration calculated at the global scale under recent CO₂ levels (see details in SI
586 section 3.2). **(B)** Simulated reduction in carbon emissions due to considering thermal acclimation of stem
587 respiration over the 21st century in two different scenarios (SSP126, SSP 585). The temperature was
588 derived from an ensemble of four future climate simulations (the land surface model is specified in
589 brackets): ACCESS-ESM1-5 (CABLE), CESM2 (CLM5), IPSL-CM6A-LR (ORCHIDEE) and
590 UKESM1-0 (JULES). The solid dotted line is the mean ensemble value (orange: under SSP126, blue:
591 under SSP585) and the shaded area represents the range of the model ensemble.



Quantity	Theoretical prediction	Measurements	Fitted coefficient	Confidence intervals		Intercept (mean ± SE)	R ²	p	df
				2.50%	97.50%				
<i>r_{s25}</i>	−0.101	In lab	−0.110	−0.143	−0.078	2.41 ± 0.74	0.27	<0.01	79
		In field	−0.101	−0.104	−0.099	1.20 ± 0.04	0.28	<0.001	4544
		All data	−0.098	−0.100	−0.095	1.16 ± 0.04	0.26	<0.001	4625
<i>r_{s,gt}</i>	−0.023	In lab	−0.028	−0.061	0.005	−0.37 ± 0.74	0.02	0.39	79
		In field	−0.019	−0.022	−0.017	−0.82 ± 0.04	0.01	<0.001	4544
		All data	−0.015	−0.018	−0.013	−0.86 ± 0.04	0.01	<0.001	4625

594 **Table 1. Global trends of stem respiration in relation to temperature.** Statistical output using the global
595 dataset shown in Figure 1. *r_{s25}* represents stem respiration standardized to the reference temperature of
596 25°C; *r_{s,gt}* represents stem respiration standardized to growth temperature. Error in Variables regression
597 analysis (EIV) was performed for field-based and lab-based data separately and also performed using all
598 data. The table provides confidence intervals, R-squared values (R²), p-values (p), and degrees of freedom
599 (df) associated with each regression model.