

SUPPLEMENTARY INFORMATION:

Global forest thickening

Marqués et al.

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S1 Data

Dataset	N	Description	Filter	Reference
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Table S1: Constituent forest dataset sizes and descriptions.

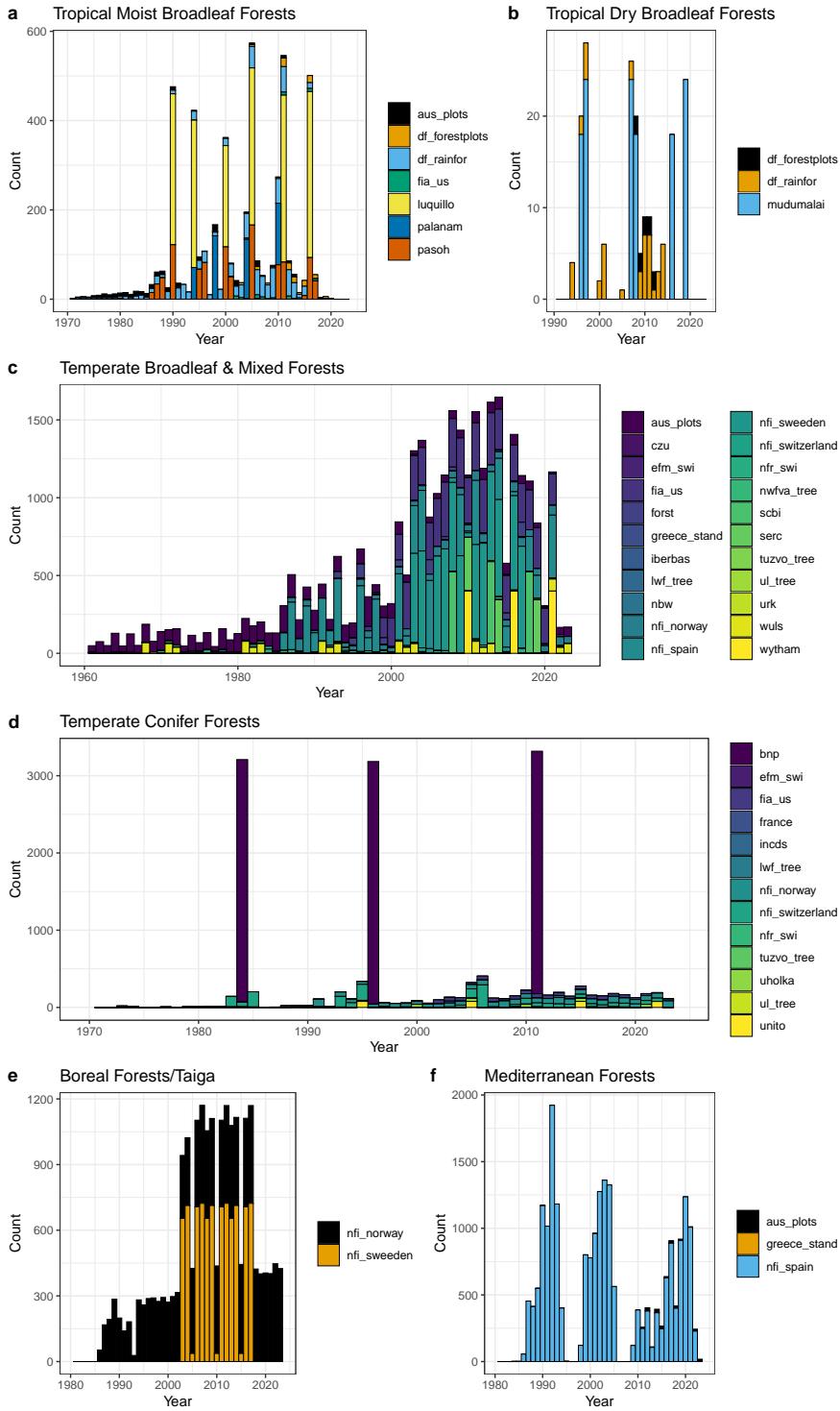


Figure S1: Distribution of forest census data over time, grouped by biome (a-f). Dataset names are explained in Tab. xxxx.

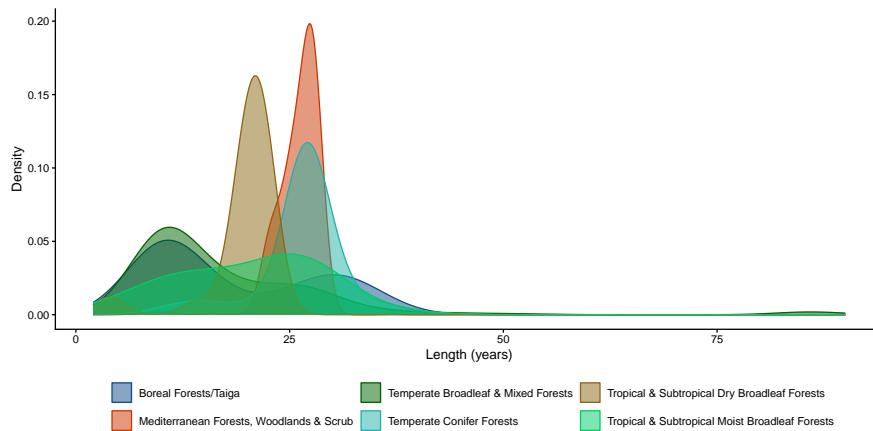


Figure S2: Distribution of the total length of the time series per forest plot, separated by biomes. The total length corresponds to the difference in the observation year of the first and last available forest inventory for each plot.

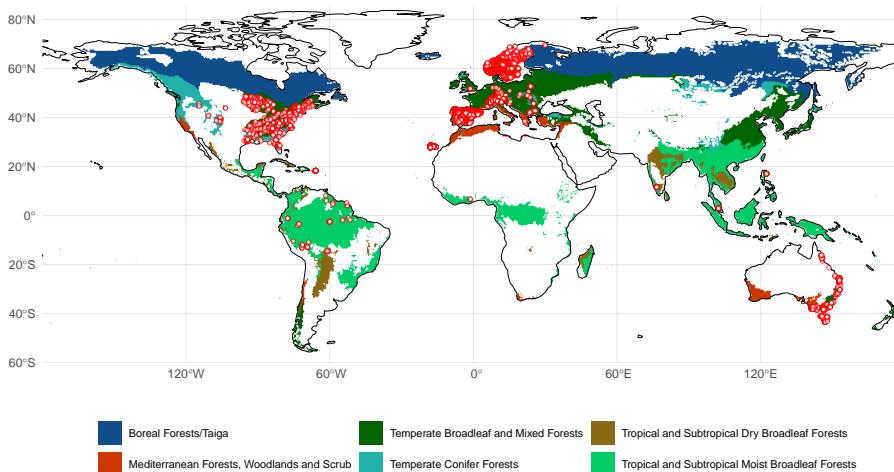


Figure S3: Distribution of forest plots (red circles) and forest biomes.

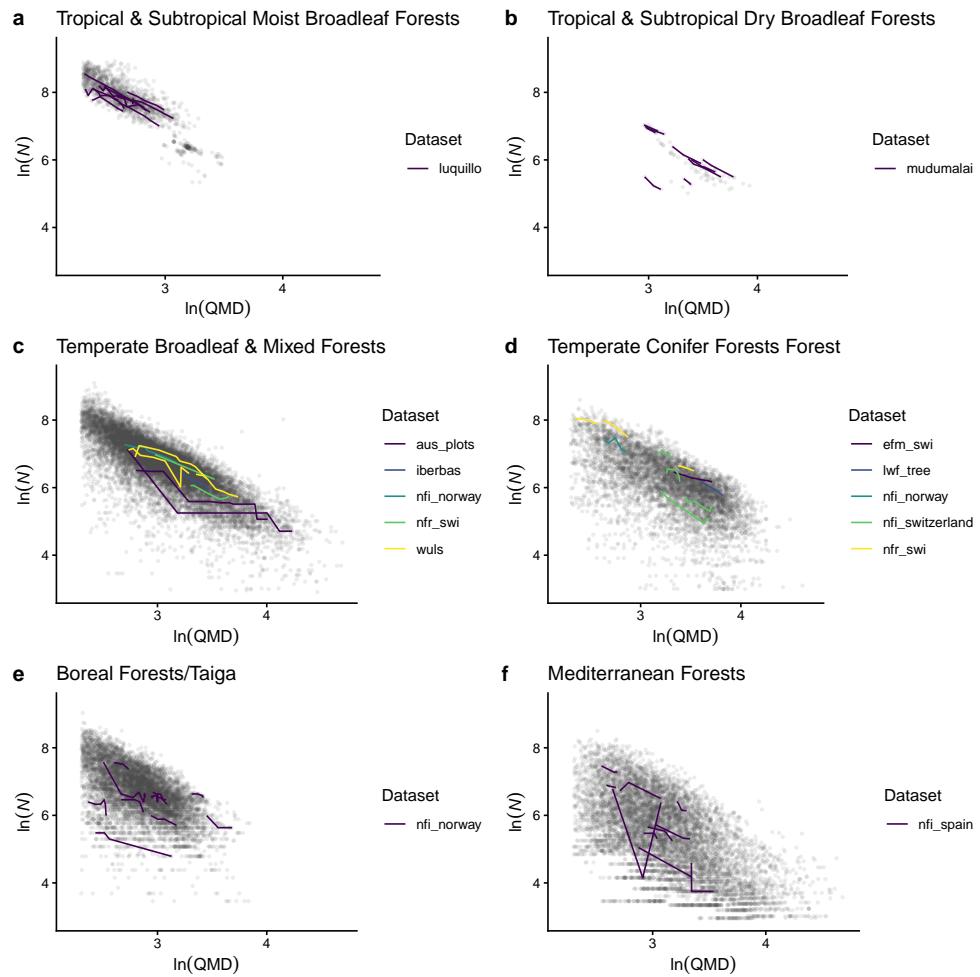


Figure S4: Self-thinning relation across biomes with example long-term forest monitoring plots highlighted.

S2 Self-thinning trends

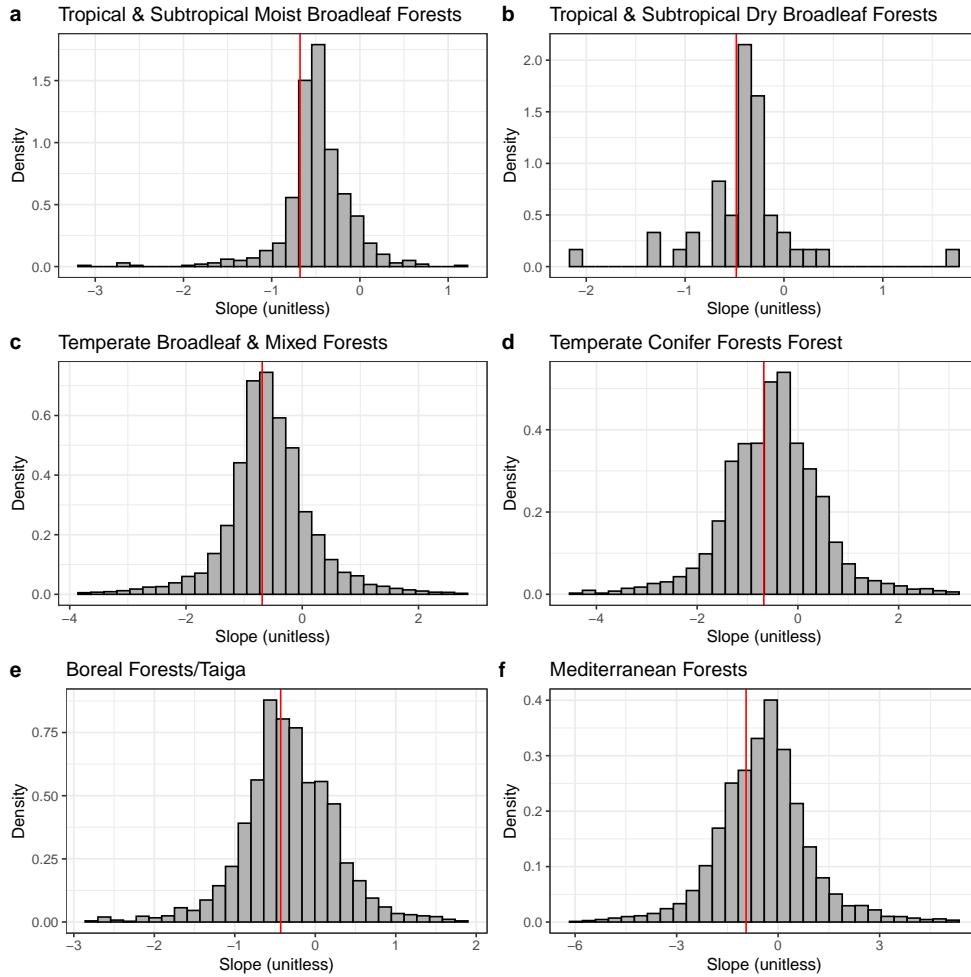


Figure S5: Self-thinning relation across biomes with example long-term forest monitoring plots highlighted.

Biome	Mean	SE
Boreal Forests/Taiga	0.30	0.06
Mediterranean Forests	2.35	0.06
Temperate Broadleaf & Mixed Forests	0.91	0.03
Temperate Conifer Forests	1.18	0.06
Tropical & Subtropical Moist Broadleaf Forests	0.16	0.07
Tropical Dry Broadleaf Forests	-0.38	0.46

Table S2: Mean estimate and standard error (SE) of percentage change (%/yr) of forest stand density (number of trees per ha) by biome, determined from quantile regressions on bootstrapped data samples.

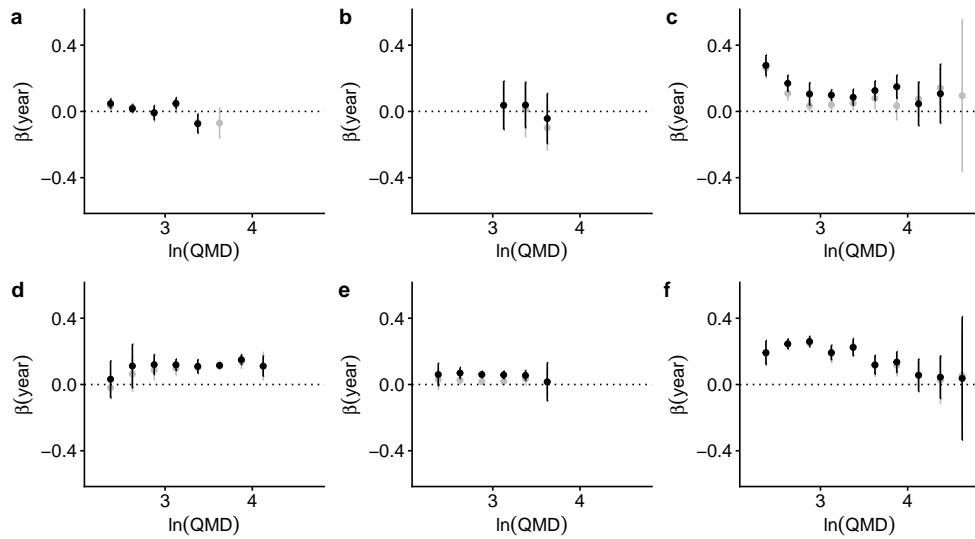


Figure S6: Effect size of 'year' within bins of quadratic mean diameter for individual biomes (a: Tropical and Subtropical Moist Broadleaf Forests, b: Tropical and Subtropical Dry Broadleaf Forests, c: Temperate Broadleaf and Mixed Forests, d: Temperate Conifer Forests Forest, e: Boreal Forests/Taiga, f: Mediterranean Forests). Grey points represent the same derived from data before the filtering of disturbance-affected plots were removed. Error bars indicate 95% confidence intervals for the coefficient.

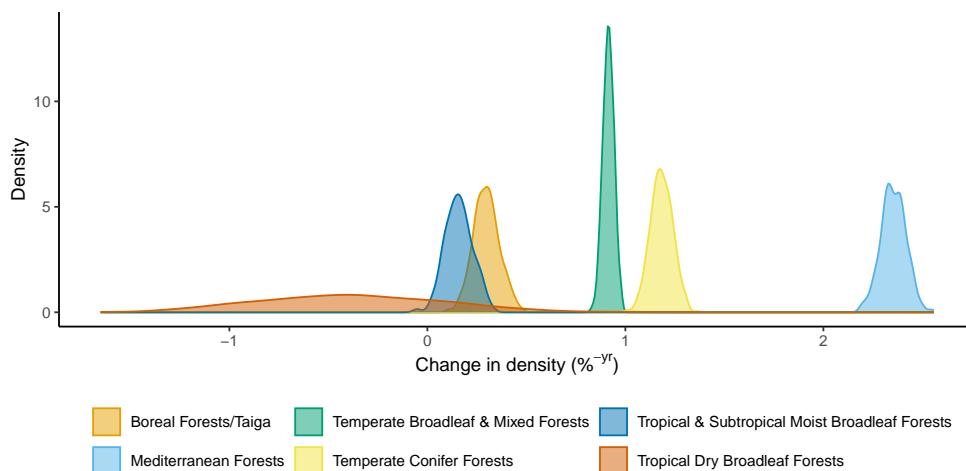


Figure S7: Distribution of percentage change (%/yr) in stand density (number of trees per ha) by biome.

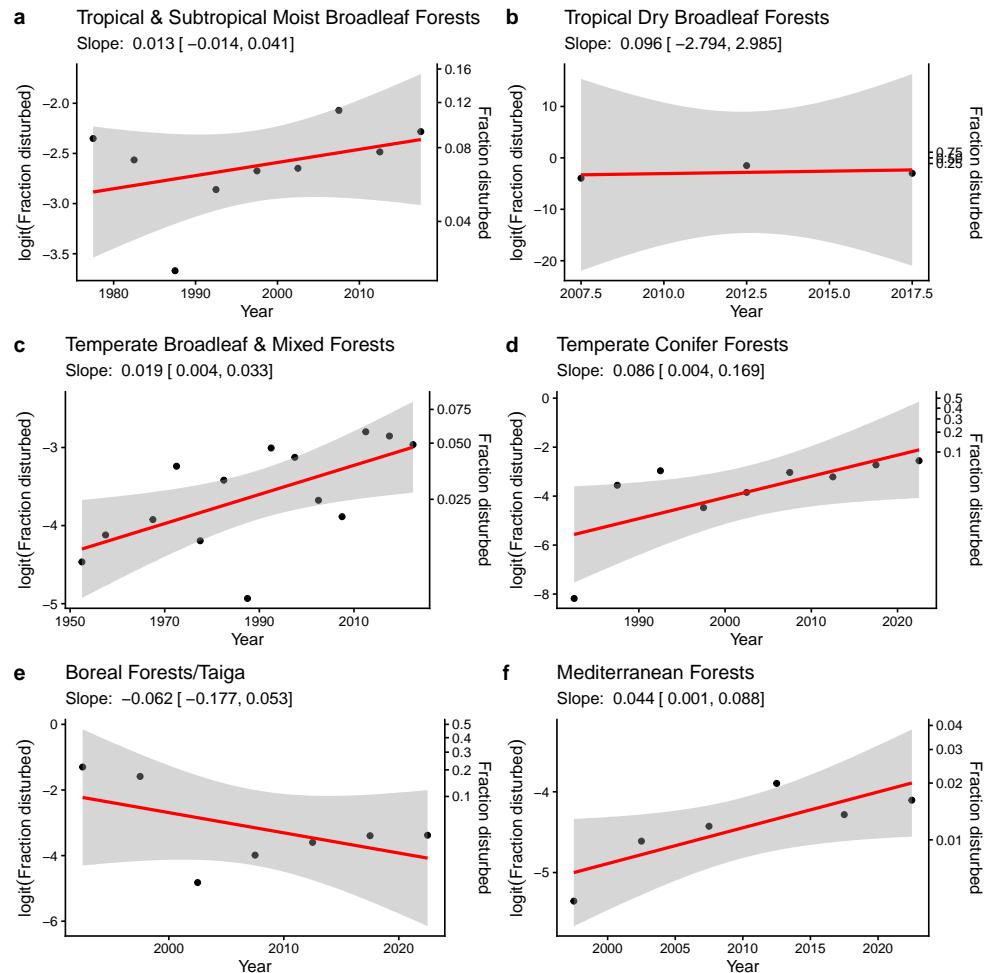


Figure S8: Trends in the fraction of disturbed forest plots, by biome. Fraction values are logit-transformed. The corresponding un-transformed values are indicated by the right y-axis in each plot. No regression fit is shown for tropical dry broadleaf forests (b) as only two points are available with non-zero values for the disturbed fraction.

S3 Environmental drivers

Table S3: Regression Results

	Complete	No PBR	No PBR, ORGC	No PBR, C:N
scale(logQMD)	-0.861*** (0.002)	-0.862*** (0.002)	-0.862*** (0.002)	-0.864*** (0.002)
scale(year)	0.129*** (0.001)	0.130*** (0.001)	0.130*** (0.001)	0.132*** (0.001)
scale(tavg)	-0.033* (0.015)	-0.026+ (0.015)	-0.007 (0.014)	-0.018 (0.015)
scale(ai)	0.086*** (0.010)	0.095*** (0.009)	0.097*** (0.009)	0.087*** (0.009)
scale(ndep)	0.153*** (0.010)	0.140*** (0.010)	0.146*** (0.010)	0.131*** (0.010)
scale(ORG C)	-0.039** (0.013)	-0.048*** (0.012)		-0.001 (0.009)
scale(PBR)	0.004 (0.008)			
scale(CNrt)	0.057*** (0.011)	0.060*** (0.011)	0.031*** (0.008)	
scale(year) × scale(tavg)	0.006** (0.002)	0.009*** (0.002)	0.013*** (0.002)	0.006** (0.002)
scale(year) × scale(ai)	-0.022*** (0.002)	-0.018*** (0.001)	-0.018*** (0.001)	-0.017*** (0.001)
scale(year) × scale(ndep)	-0.016*** (0.002)	-0.015*** (0.002)	-0.015*** (0.002)	-0.011*** (0.001)
scale(year) × scale(ORG C)	-0.012*** (0.002)	-0.011*** (0.002)		-0.028*** (0.002)
scale(year) × scale(PBR)	0.006*** (0.002)			
scale(year) × scale(CNrt)	-0.021*** (0.002)	-0.023*** (0.002)	-0.028*** (0.001)	
SD (Observations)	0.176	0.178	0.178	0.178
Num.Obs.	36133	37652	37652	37652
R2 Marg.	0.521	0.530	0.531	0.527
R2 Cond.	0.980	0.980	0.980	0.980
AIC	17693.1	19142.8	19162.9	19315.9
BIC	17846.0	19279.3	19282.4	19435.4
ICC	1.0	1.0	1.0	1.0
RMSE	0.15	0.15	0.15	0.15

S4 Global C sink

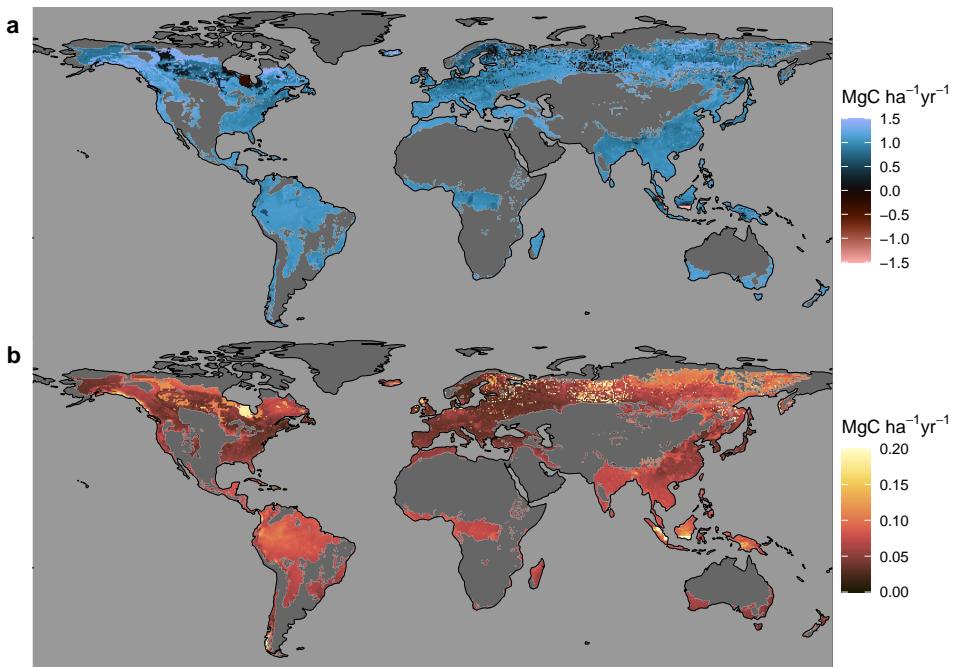


Figure S9: (a) C sink in aboveground biomass due to temporal changes in the self-thinning relationship. (b) Standard deviation of estimates across bootstraps. Values are expressed per unit forest area ($\text{gC m}^{-2} \text{yr}^{-1}$).

References

- Aranjuelo, I., Ebbets, A. L., Evans, R. D., Tissue, D. T., Nogues, S., van Gestel, N. C., Payton, P., Ebbert, V., Adams, W. W., Nowak, R. S., and Smith, S. D.: Maintenance of C Sinks Sustains Enhanced C Assimilation during Long-Term Exposure to Elevated [CO₂] in Mojave Desert Shrubs, *Oecologia*, pp. 339–354, <https://doi.org/10.1007/s00442-011-1996-y>, 2011.
- Bernacchi, C. J., Calfapietra, C., Davey, P. A., Wittig, V. E., Scarascia-Mugnozza, G. E., Raines, C. A., and Long, S. P.: Photosynthesis and Stomatal Conductance Responses of Poplars to Free-Air CO₂ Enrichment (PopFACE) during the First Growth Cycle and Immediately Following Coppice, *The New Phytologist*, 159, 609–621, <https://doi.org/10.1046/j.1469-8137.2003.00850.x>, 2003.
- Bernacchi, C. J., Morgan, P. B., Ort, D. R., and Long, S. P.: The Growth of Soybean under Free Air [CO₂] Enrichment (FACE) Stimulates Photosynthesis While Decreasing in Vivo Rubisco Capacity, *Planta*, 220, 434–446, <https://doi.org/10.1007/s00425-004-1320-8>, 2005.
- Boesgaard, K. S. and Ro-Poulsen, H.: Long-Term Ecophysiological Responses to Climate Change, Technical University of Denmark, Kgs. Lyngby, 2013.
- Borenstein, M.: Effect sizes for continuous data, in: The handbook of research synthesis and meta-analysis, 2nd ed, pp. 221–235, Russell Sage Foundation, New York, NY, US, 2009.
- Calfapietra, C., Wiberley, A. E., Falbel, T. G., Linskey, A. R., Mugnozza, G. S., Karnosky, D. F., Loreto, F., and Sharkey, T. D.: Isoprene Synthase Expression and Protein Levels Are Reduced under Elevated O₃ but Not under Elevated CO₂ (FACE) in Field-Grown Aspen Trees, *Plant, Cell & Environment*, 30, 654–661, <https://doi.org/10.1111/j.1365-3040.2007.01646.x>, 2007.
- Calfapietra, C., Scarascia Mugnozza, G., Karnosky, D. F., Loreto, F., and Sharkey, T. D.: Isoprene Emission Rates under Elevated CO₂ and O₃ in Two Field-Grown Aspen Clones Differing in Their Sensitivity to O₃, *The New Phytologist*, 179, 55–61, <https://doi.org/10.1111/j.1469-8137.2008.02493.x>, 2008.
- Crous, K. Y., Reich, P. B., Hunter, M. D., and Ellsworth, D. S.: Maintenance of Leaf N Controls the Photosynthetic CO₂ Response of Grassland Species Exposed to 9 Years of Free-air CO₂ Enrichment, *Global Change Biology*, 16, 2076–2088, <https://doi.org/10.1111/j.1365-2486.2009.02058.x>, 2010.
- Cseke, L. J., Tsai, C.-J., Rogers, A., Nelsen, M. P., White, H. L., Karnosky, D. F., and Podila, G. K.: Transcriptomic Comparison in the Leaves of Two Aspen Genotypes Having Similar Carbon Assimilation Rates but Different Partitioning Patterns under Elevated [CO₂], *New Phytologist*, 182, 891–911, <https://doi.org/10.1111/j.1469-8137.2009.02812.x>, 2009.
- Darbah, J. N., Kubiske, M. E., Nelson, N., Kets, K., Riikonen, J., Sober, A., Rouse, L., and Karnosky, D. F.: Will Photosynthetic Capacity of Aspen Trees Acclimate after Long-Term Exposure to Elevated CO₂ and O₃?, *Environmental Pollution*, 158, 983–991, <https://doi.org/10.1016/j.envpol.2009.10.022>, 2010.

- Dawes, M. A., Hagedorn, F., Handa, I. T., Streit, K., Ekblad, A., Rixen, C., Körner, C., and Hättenschwiler, S.: An Alpine Treeline in a Carbon Dioxide-Rich World: Synthesis of a Nine-Year Free-Air Carbon Dioxide Enrichment Study, *Oecologia*, 171, 623–637, <https://doi.org/10.1007/s00442-012-2576-5>, 2013.
- Dermody, O., Long, S. P., and DeLucia, E. H.: How Does Elevated CO₂ or Ozone Affect the Leaf-Area Index of Soybean When Applied Independently?, *The New Phytologist*, 169, 145–155, <https://doi.org/10.1111/j.1469-8137.2005.01565.x>, 2006.
- Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Bakker, D. C. E., Hauck, J., Le Quéré, C., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Anthoni, P., Bates, N. R., Becker, M., Bellouin, N., Bopp, L., Chau, T. T. T., Chevallier, F., Chini, L. P., Cronin, M., Currie, K. I., Decharme, B., Djeutchouang, L. M., Dou, X., Evans, W., Feely, R. A., Feng, L., Gasser, T., Gilfillan, D., Gkritzalis, T., Grassi, G., Gregor, L., Gruber, N., Gürses, O., Harris, I., Houghton, R. A., Hurt, G. C., Iida, Y., Ilyina, T., Luijkx, I. T., Jain, A., Jones, S. D., Kato, E., Kennedy, D., Klein Goldewijk, K., Knauer, J., Korsbakken, J. I., Kötzinger, A., Landschützer, P., Lauvset, S. K., Lefèvre, N., Lienert, S., Liu, J., Marland, G., McGuire, P. C., Melton, J. R., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S.-I., Niwa, Y., Ono, T., Pierrot, D., Poulter, B., Rehder, G., Resplandy, L., Robertson, E., Rödenbeck, C., Rosan, T. M., Schwinger, J., Schwingshakel, C., Séférian, R., Sutton, A. J., Sweeney, C., Tanhua, T., Tans, P. P., Tian, H., Tilbrook, B., Tubiello, F., van der Werf, G. R., Vuichard, N., Wada, C., Wanninkhof, R., Watson, A. J., Willis, D., Wiltshire, A. J., Yuan, W., Yue, C., Yue, X., Zaehle, S., and Zeng, J.: Global Carbon Budget 2021, *Earth System Science Data*, 14, 1917–2005, <https://doi.org/10.5194/essd-14-1917-2022>, URL <https://essd.copernicus.org/articles/14/1917/2022/>, 2022.
- Gunderson, C. A., Sholtis, J. D., Wullschleger, S. D., Tissue, D. T., Hanson, P. J., and Norby, R. J.: Environmental and Stomatal Control of Photosynthetic Enhancement in the Canopy of a Sweetgum (*Liquidambar Styraciflua* L.) Plantation during 3 Years of CO₂ Enrichment, *Plant, Cell & Environment*, 25, 379–393, <https://doi.org/10.1046/j.0016-8025.2001.00816.x>, 2002.
- Guo, J., Trotter, C. M., and Newton, P. C. D.: Initial Observations of Increased Requirements for Light-Energy Dissipation in Ryegrass (*Lolium Perenne*) When Source / Sink Ratios Become High at a Naturally Grazed Free Air CO₂ Enrichment (FACE) Site, *Functional plant biology: FPB*, 33, 1045–1053, <https://doi.org/10.1071/FP06168>, 2006.
- Hamerlynck, E., Huxman, T., Nowak, R., Redar, S. P., Loik, M., Jordan, D. N., Zitzer, S., Coleman, J., Seemann, J., and Smith, S. D.: Photosynthetic Responses of *Larrea Tridentata* to a Step-Increase in Atmospheric CO₂ at the Nevada Desert FACE Facility, *Journal of Arid Environments*, <https://doi.org/10.1006/jare.1999.0615>, 2000.
- Handa, I. T., Körner, C., and Hättenschwiler, S.: A Test of the Tree-Line Carbon Limitation Hypothesis by in Situ CO₂ Enrichment and Defoliation, *Ecology*, 86, Nr. 5, 1288–1300, <https://doi.org/10.1890/04-0711>, 2005.

- Hättenschwiler, S., Handa, I. T., Egli, L., Asshoff, R., Ammann, W., and Körner, C.: Atmospheric CO₂ Enrichment of Alpine Treeline Conifers, *New Phytologist*, 156, 363–375, <https://doi.org/10.1046/j.1469-8137.2002.00537.x>, 2002.
- Hovenden, M. J.: Photosynthesis of Coppicing Poplar Clones in a Free-Air CO₂ Enrichment (FACE) Experiment in a Short-Rotation Forest, *Functional plant biology: FPB*, 30, 391–400, <https://doi.org/10.1071/FP02233>, 2003.
- Hoyt, A. C. D. R. . W. T.: MAd: Meta-Analysis with Mean Differences, URL <https://CRAN.R-project.org/package=MAd>, 2014.
- Huxman, T. E. and Smith, S. D.: Photosynthesis in an Invasive Grass and Native Forb at Elevated CO₂ during an El Niño Year in the Mojave Desert, *Oecologia*, 128, 193–201, <https://doi.org/10.1007/s004420100658>, 2001.
- Karnosky, D. F., Zak, D. R., Pregitzer, K. S., Awmack, C. S., Bockheim, J. G., Dickson, R. E., Hendrey, G. R., Host, G. E., King, J. S., Kopper, B. J., Kruger, E. L., Kubiske, M. E., Lindroth, R. L., Mattson, W. J., McDonald, E. P., Noormets, A., Oksanen, E., Parsons, W. F. J., Percy, K. E., Podila, G. K., Riemenschneider, D. E., Sharma, P., Thakur, R., Sôber, A., Sôber, J., Jones, W. S., Anttonen, S., Vapaavuori, E., Mankovska, B., Heilman, W., and Isebrands, J. G.: Tropospheric O₃ Moderates Responses of Temperate Hardwood Forests to Elevated CO₂: A Synthesis of Molecular to Ecosystem Results from the Aspen FACE Project, *Functional Ecology*, 17, 289–304, <https://doi.org/10.1046/j.1365-2435.2003.00733.x>, 2003.
- Kets, K., Darbah, J. N., Sober, A., Riikonen, J., Sober, J., and Karnosky, D. F.: Diurnal Changes in Photosynthetic Parameters of *Populus tremuloides*, Modulated by Elevated Concentrations of CO₂ and/or O₃ and Daily Climatic Variation, *Environmental Pollution*, 158, 1000–1007, <https://doi.org/10.1016/j.envpol.2009.09.001>, 2010.
- Lee, T. D., Tjoelker, M. G., Ellsworth, D. S., and Reich, P. B.: Leaf Gas Exchange Responses of 13 Prairie Grassland Species to Elevated CO₂ and Increased Nitrogen Supply, *New Phytologist*, 150, 405–418, <https://doi.org/10.1046/j.1469-8137.2001.00095.x>, 2001.
- Lee, T. D., Barrott, S. H., and Reich, P. B.: Photosynthetic Responses of 13 Grassland Species across 11 Years of Free-Air CO₂ Enrichment Is Modest, Consistent and Independent of N Supply, *Global Change Biology*, 17, 2893–2904, <https://doi.org/10.1111/j.1365-2486.2011.02435.x>, 2011.
- Liu, J., Zhou, G., Xu, Z., Duan, H., Li, Y., and Zhang, D.: Photosynthesis Acclimation, Leaf Nitrogen Concentration, and Growth of Four Tree Species over 3 Years in Response to Elevated Carbon Dioxide and Nitrogen Treatment in Subtropical China, *Journal of Soils and Sediments*, 11, 1155–1164, <https://doi.org/10.1007/s11368-011-0398-4>, 2011.
- Monson, R. K., Trahan, N., Rosenstiel, T. N., Veres, P., Moore, D., Wilkinson, M., Norby, R. J., Volder, A., Tjoelker, M. G., Briske, D. D., Karnosky, D. F., and Fall, R.: Isoprene Emission from Terrestrial Ecosystems in Response to Global Change: Minding the Gap between Models and Observations, *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, 365, 1677–1695, <https://doi.org/10.1098/rsta.2007.2038>, 2007.

- Noormets, A., McDonald, E. P., Dickson, R. E., Kruger, E. L., Sôber, A., Isebrands, J., and Karnosky, D. F.: The Effect of Elevated Carbon Dioxide and Ozone on Leaf- and Branch-Level Photosynthesis and Potential Plant-Level Carbon Gain in Aspen, *Trees*, 15, 262–270, <https://doi.org/10.1007/s004680100102>, 2001.
- Noormets, A., Kull, O., Sôber, A., Kubiske, M. E., and Karnosky, D. F.: Elevated CO₂ Response of Photosynthesis Depends on Ozone Concentration in Aspen, *Environmental Pollution* (Barking, Essex: 1987), 158, 992–999, <https://doi.org/10.1016/j.envpol.2009.10.009>, 2010.
- Riikonen, J., Kets, K., Darbah, J., Oksanen, E., Sober, A., Vapaavuori, E., Kubiske, M. E., Nelson, N., and Karnosky, D. F.: Carbon Gain and Bud Physiology in *Populus tremuloides* and *Betula papyrifera* Grown under Long-Term Exposure to Elevated Concentrations of CO₂ and O₃, *Tree Physiology*, 28, 243–254, <https://doi.org/10.1093/treephys/28.2.243>, 2008.
- Sholtis, J. D., Gunderson, C. A., Norby, R. J., and Tissue, D. T.: Persistent Stimulation of Photosynthesis by Elevated CO₂ in a Sweetgum (*Liquidambar styraciflua*) Forest Stand, *New Phytologist*, 162, 343–354, <https://doi.org/10.1111/j.1469-8137.2004.01028.x>, 2004.
- Sitch, S., O'Sullivan, M., Robertson, E., Friedlingstein, P., Albergel, C., Anthoni, P., Arneth, A., Arora, V. K., Bastos, A., Bastrikov, V., Bellouin, N., Canadell, J. G., Chini, L., Ciais, P., Falk, S., Harris, I., Hurt, G., Ito, A., Jain, A. K., Jones, M. W., Joos, F., Kato, E., Kennedy, D., Klein Goldewijk, K., Kluzek, E., Knauer, J., Lawrence, P. J., Lombardozzi, D., Melton, J. R., Nabel, J. E. M. S., Pan, N., Peylin, P., Pongratz, J., Poulter, B., Rosan, T. M., Sun, Q., Tian, H., Walker, A. P., Weber, U., Yuan, W., Yue, X., and Zaehle, S.: Trends and Drivers of Terrestrial Sources and Sinks of Carbon Dioxide: An Overview of the TRENDY Project, *Global Biogeochemical Cycles*, 38, e2024GB008102, <https://doi.org/10.1029/2024GB008102>, URL <https://onlinelibrary.wiley.com/doi/abs/10.1029/2024GB008102>, _eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1029/2024GB008102>, 2024.
- Strengbom, J. and Reich, P. B.: Elevated [CO₂] and Increased N Supply Reduce Leaf Disease and Related Photosynthetic Impacts on *Solidago rigida*, *Oecologia*, 149, 519–525, <https://doi.org/10.1007/s00442-006-0458-4>, 2006.
- Takeuchi, Y., Kubiske, M. E., Isebrands, J. G., Pregitzer, K., Hendrey, G., and Karnosky, D. F.: Photosynthesis, Light and Nitrogen Relationships in a Young Deciduous Forest Canopy under Open-air CO₂ Enrichment, *Plant, Cell & Environment*, 24, 1257–1268, <https://doi.org/10.1046/j.0016-8025.2001.00787.x>, 2001.
- Tjoelker, M. G., Craine, J. M., Wedin, D., Reich, P. B., and Tilman, D.: Linking Leaf and Root Trait Syndromes among 39 Grassland and Savannah Species, *New Phytologist*, 167, 493–508, <https://doi.org/10.1111/j.1469-8137.2005.01428.x>, 2005.
- Tricker, P., Trewin, H., Kull, O., Clarkson, G., Eensalu, E., Tallis, M., Colella, A., Doncaster, C., Sabatti, M., and Taylor, G.: Stomatal Conductance and Not Stomatal Density Determines the Long-Term Reduction in Leaf Transpiration of Poplar in Elevated CO₂, *Oecologia*, 143, 652–660, <https://doi.org/10.1007/s00442-005-0025-4>, 2005.

- Van Sundert, K., Leuzinger, S., Bader, M. K., Chang, S. X., De Kauwe, M. G., Dukes, J. S., Langley, J. A., Ma, Z., Mariën, B., Reynaert, S., Ru, J., Song, J., Stocker, B., Terrer, C., Thoresen, J., Vanuytrecht, E., Wan, S., Yue, K., and Vicca, S.: When things get MESI: The Manipulation Experiments Synthesis Initiative—A coordinated effort to synthesize terrestrial global change experiments, *Global Change Biology*, 29, 1922–1938, <https://doi.org/10.1111/gcb.16585>, URL <https://onlinelibrary.wiley.com/doi/10.1111/gcb.16585>, 2023.
- Viechtbauer, W.: Conducting Meta-Analyses in R with the metafor Package, *Journal of Statistical Software*, 36, 1–48, <https://doi.org/10.18637/jss.v036.i03>, URL <https://doi.org/10.18637/jss.v036.i03>, 2010.
- Von Caemmerer, S., Ghannoum, O., Conroy, J. P., Clark, H., and Newton, P. C. D.: Photosynthetic Responses of Temperate Species to Free Air CO₂ Enrichment (FACE) in a Grazed New Zealand Pasture, *Functional Plant Biology*, 28, 439, <https://doi.org/10.1071/PP01009>, 2001.
- Warren, J. M., Jensen, A. M., Medlyn, B. E., Norby, R. J., and Tissue, D. T.: Carbon Dioxide Stimulation of Photosynthesis in Liquidambar Styraciflua Is Not Sustained during a 12-Year Field Experiment, *AoB PLANTS*, 7, plu074, <https://doi.org/10.1093/aobpla/plu074>, 2015.