



HAL
open science

Human activities shape global patterns of decomposition rates in rivers

Scott Tiegs, Krista A Capps, David Costello, John Paul Schmidt, Christopher J Patrick, J. Follstad Shah, Carri J Leroy, Vicenç Acuña, Ricardo Albariño, Daniel Allen, et al.

► To cite this version:

Scott Tiegs, Krista A Capps, David Costello, John Paul Schmidt, Christopher J Patrick, et al.. Human activities shape global patterns of decomposition rates in rivers. *Science*, 2024, 384 (6701), pp.1191-1195. 10.1126/science.adn1262 . hal-04652223

HAL Id: hal-04652223

<https://hal.science/hal-04652223v1>

Submitted on 14 Nov 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

Human activities shape global patterns of decomposition rates in rivers

Authors: S. D. Tiegs^{1*#}, K. A. Capps^{2,3*#}, D. M. Costello^{4*#}, J. P. Schmidt^{2*}, C. J. Patrick^{5*}, J. J. Follstad Shah⁶, C. J. LeRoy⁷, and the CELLDEX Consortium[†]

¹ Department of Biological Sciences, Oakland University; Rochester, 48309, U.S.A.

² Odum School of Ecology, University of Georgia; Athens, 30602, U.S.A.

³ Savannah River Ecology Laboratory, University of Georgia; Aiken, 29802, U.S.A.

⁴ Department of Biological Sciences, Kent State University; Kent, 44242, U.S.A

⁵ Virginia Institute of Marine Science, Coastal Ocean Processes Section, William & Mary; Gloucester Point, 23062, U.S.A.

⁶ School of the Environment, Society, and Sustainability; University of Utah, Salt Lake City, 84112, U.S.A.

⁷ Environmental Studies Program, The Evergreen State College; Olympia, 98505, U.S.A. †CELLDEX Consortium authors and affiliations are listed in the supplementary materials.

*Corresponding authors. Email: tiegs@oakland.edu, kcapps@uga.edu, dcostel3@kent.edu, jps@uga.edu, cpatrick@vims.edu

#These authors contributed equally to this work.

Abstract:

Rivers and streams contribute to global carbon cycling by decomposing immense quantities of terrestrial plant matter. However, decomposition rates are highly variable, and large-scale patterns and drivers of this process remain poorly understood. Using a cellulose-based assay to reflect the primary constituent of plant detritus, we generated a predictive model (81% variance explained) for cellulose-decomposition rates across 514 globally distributed streams. A large number of variables were important for predicting decomposition, highlighting the complexity of this process at the global scale. Predicted cellulose-decomposition rates, when combined with genus-level litter-quality attributes, explain published leaf-litter-decomposition rates with impressive accuracy (70% variance explained). Our global map provides estimates of rates

across vast understudied areas of Earth, and reveals rapid decomposition across continental-scale areas dominated by human activities.

One-Sentence Summary: By integrating big data and a global experiment, we predict organic-matter decomposition in rivers worldwide.

5

Main Text:

Earth's terrestrial ecosystems produce over 100 billion tons of plant detritus annually (1, 2), and the fates of this organic matter – for example, long-term storage, mineralization to greenhouse gasses, or incorporation into stream food webs – depend on the rate at which it is decomposed.

10 River ecosystems are carbon-processing hotspots (3, 4), receiving 0.72 billion tons of terrestrial carbon per year (2), an amount that is disproportionately important relative to the small fraction of non-glaciated land area (0.58%) rivers occupy (5). Rivers connect terrestrial ecosystems with aquatic storage compartments including floodplains, lakes and oceans, playing vital roles in the global carbon cycle, and functioning both as organic-matter conduits and reactors. Despite the
15 widely recognized importance of flowing waters in global carbon cycling (6–8), our understanding of variation in organic-matter-decomposition rates and their drivers at large spatial scales is still limited (2).

Large-scale spatial variation in organic-matter decomposition in rivers and streams has been estimated by comparing leaf-litter-decomposition rates from studies conducted in regions with
20 contrasting climates (9, 10), conducting literature reviews of local field studies (11), developing conceptual models (12, 13) and performing meta-analyses (14, 15). Coordinated, distributed experiments (16–20) have been particularly insightful by generating directly comparable data across broad geographic areas and identifying coarse-resolution explanatory variables of

decomposition rates in rivers, including differences in decomposer communities and biomes.

Still, we lack a comprehensive understanding of how drivers such as climate, geology,

vegetation, water quality, and soils interact to govern organic-matter decomposition at large

scales. Such knowledge gaps are particularly evident across the tropics and in lower-income

5 economies – ecologically important areas where rivers are grossly understudied relative to those

in northern temperate zones. Quantifying patterns and controls of decomposition in these areas is

critical, however, because much of Earth’s terrestrial plant matter is annually produced in

tropical forests (net primary production 16.0–23.1 billion tons of carbon) (21, 22), and tropical

rivers deliver 48-64% of the carbon moving from rivers to the ocean (23).

10 Effectively modeling carbon dynamics at the global scale – including areas where field data are

scarce – requires a more mechanistic and process-based understanding of the many

environmental and biotic factors that drive organic-matter decomposition. Accurate estimates

generated by combining existing empirical measurements with fine-scale geospatial and

environmental data can provide multiple benefits. They can reduce the need for data collection

15 from remote or difficult-to-access regions, subsequently generating baseline estimates for

decomposition in understudied areas of the world. Global-scale predictions also contribute to a

finer-scale understanding of decomposition and support efforts to model planetary carbon

dynamics. Models that can accurately predict current *in-situ* decomposition rates across space are

particularly valuable, enabling manipulation of environmental drivers *in silico* to predict impacts

20 under scenarios of future global environmental change.

Here, we present a predictive model fitted with global data from CELLDEX (Cellulose

Decomposition Experiment), a coordinated, distributed experiment on cellulose decomposition

in rivers designed to reveal previously undocumented patterns in decomposition rates and the key factors driving this fundamental ecosystem-level process. Decomposition of cellulose – the most abundant organic polymer on the planet and a main constituent of plant litter – was quantified by over 150 investigators by using a common and well-established cellulose-decomposition assay (24). The ‘cotton-strip assay’ is a standardized approach for measuring decomposition by using a readily available woven cotton fabric (Artist’s canvas) that is comprised of 95% cellulose. The loss of tensile strength of the fabric is measured, a process that is strongly correlated with the microbial catabolism of cellulose (25). We performed the assay in 514 flowing-water ecosystems at georeferenced field sites on all seven continents, spanning 135° of latitude and each of Earth’s major terrestrial biomes (19, 20). We used high-resolution (15 arcsecond) climate, soil, geology, vegetation, and physicochemical data (101 explanatory variables total) in a boosted-regression tree (BRT) algorithm to develop the first global, high-resolution predictive model of organic-matter decomposition in rivers. We then tested the utility of the cellulose model by using predicted cellulose-decomposition rates and genus-level leaf-litter chemistry traits to explain 895 leaf-litter decomposition estimates from studies conducted at 559 unique locations across the globe. We found that cellulose-decomposition rates are an excellent proxy for litter-decomposition rates. Further, our models indicate the physicochemical factors at river and watershed scales interact with characteristics of the organic matter being

decomposed (e.g., leaf-litter chemistry) to create heterogenous spatial patterns in riverine decomposition across the planet.

Climate, geology, soils, and water quality explain cellulose decomposition rates.

Climate, geology, soil, and water-quality variables explain 81% of variance in field
5 measurements of *in-situ* cellulose decomposition. Because a standardized cellulose substrate was used at all field sites, observed variation in decomposition rates can be attributed unequivocally to the activity of microbial communities and environmental drivers. Prior efforts have explained broad variation in decomposition rates across riverine ecosystems as a function of exogenous factors such as temperature (14, 19) and concentrations of dissolved nutrients (17, 20, 26), as
10 well as litter traits (15, 27, 28). Our model supports those findings and shows that climatic and water-quality parameters are among the most important explanatory variables of decomposition rates (Fig. 1). However, a relatively large number of explanatory variables (n=26) have importance values greater than 1.0 (table s1), and no single variable contributes >15% to the explanatory power of the model (table s1). This result reveals the complexity of the many drivers
15 that influence organic-matter decomposition at the global scale.

Top explanatory variables of cellulose decomposition include expected attributes like mean daily water temperature (importance value [IV]=14.0; Fig. 1A), nitrogen and phosphorus availability (IV=6.7 and 4.9, respectively; Fig. 1C & D), and mean annual air temperature (IV=2.5; Fig. 1F). Our data and approach also highlight watershed-level characteristics that have been given little
20 attention previously, such as sub-watershed lake area (limnicity) (IV=6.9; Fig. 1B), actual evapotranspiration in the watershed (IV=4.4; Fig. 1E), and the chemical and physical properties of soil (table s1). Subwatershed lake area was a high-ranking variable, and its negative

relationship with decomposition rates may be explained by the disproportionately greater abundance of lakes at high northern latitudes where water temperatures are low (Fig. 1B).

Alternatively, lower nutrient concentrations and suppressed hydrological variability may have also contributed to the negative influence of limnity on decomposition. Although our study

5 sites were selected to have minimal human impacts relative to their region of study (19), variables associated with anthropogenic development, such as dissolved-nutrient yields, crop-land extent (IV=2.0), population count (IV=1.3), and river regulation (IV=1.3), still emerge as important (table s1). Notably, relationships between explanatory variables and decomposition rates are frequently non-linear, revealing thresholds beyond which there are abrupt changes in
10 decomposition rates (e.g., Fig. 1B, D, & E). Water temperature has a strong positive effect on cellulose decomposition (Fig. 1A), and there is an optimal range (5-13 °C) of annual air temperature with estimated lower rates in both cooler and warmer watersheds (Fig. 1F).

Extrapolating to global patterns of decomposition rates

Our model and map of riverine cellulose decomposition reveals pronounced, large-scale spatial
15 patterns of organic-matter processing (Fig. 2). Rates generally increase with decreasing latitude, with rapid rates in tropical regions (e.g., Central America, Amazon basin, Western Africa, Indo-Pacific) and areas characterized by volcanic activity and young soils, an effect previously documented only at more local scales (29). Importantly, fluvial ecosystems in these regions are among the least studied on the planet (Fig. 2, inset), yet they have high rates of terrestrial
20 primary production (22) and carbon export to the ocean (23). Vast areas in middle latitudes with ubiquitous human impacts – central Europe, eastern China, central North America, southeastern South America, and Japan – also support elevated decomposition rates, strongly suggesting

continental-scale human impacts on carbon cycling in rivers. In contrast, areas of boreal forests, characterized by short growing seasons, low temperatures, and peaty, acidic, water-logged soils, exhibit slower rates of organic-matter decomposition, especially in northern Asia, eastern Scandinavia, and northeastern Canada.

5 *Validating predicted cellulose-decomposition rates with leaf-litter-decomposition rates*

Recognizing that the substrate used in our standardized decomposition assay (cellulose as cotton fabric) lacks the chemical complexity of organic matter that naturally enters running waters, we also tested how accurately our modeling approach could explain variation in the decomposition rates of terrestrial leaf litter in rivers reported by ecologists worldwide. To this end we
10 independently validated model forecasts using 895 unique litter-decomposition rates from 559 locations and representing 35 genera of terrestrial plants (27). We also used leaf- and litter-trait data at the genus level (30, 31) and experimental conditions (14, 27) as explanatory variables to account for variation among decomposition estimates resulting from differences in leaf-litter quality (e.g., lignin, hemicellulose, tannin, nutrient content) and the feeding activity of
15 invertebrates (Figure 3A, table S2). Our cellulose-decomposition model predictions coupled with litter traits account for 70% of the variation in leaf-litter decomposition. Importantly, the explanatory power of this model is overwhelmingly driven by predicted rates of cellulose decomposition (IV=39.5), despite the stark differences in quality between the cellulose substrate and natural litter (Fig 3A, table S2). These results provide strong support for the critical

influence that environmental drivers have in regulating riverine litter decomposition, including the drivers impacted by anthropogenic activities.

Prior research at large scales has stressed the importance of litter quality as the predominant control of decomposition rates in rivers (15). Our results demonstrate that in addition to leaf-
5 litter traits, environmental factors, such as temperature and nutrient availability, are critically important in regulating decomposition rates at larger spatial scales. Our validation model also reveals that invertebrate access to leaves, as assessed by experimentally manipulating litter-bag mesh size, greatly increase the rate of decomposition in all but the fastest decomposing leaves (Fig. 3A). Finally, litter chemistry contributes to the explanatory power of the model in expected
10 ways, with plant genera that are characterized by high lignin content (IV=11.9; Fig. 3B) and low litter-nitrogen content (C:N, IV=5.45 and N, IV=5.23; Fig. 3C & D) decomposing more slowly. Other litter traits (e.g., P content, cellulose) provide little additional explanatory power and no leaf traits explain more variation than expected by chance (table s2). It is well recognized that leaf-litter chemistry can vary among individuals within a species (32, 33) and even individual
15 leaves from a single tree (34); thus, our model may underestimate the importance of individual-level variation in leaf and litter chemistry in driving decomposition. Greater measurement and reporting of litter chemistry, especially nitrogen and lignin content will improve understanding of endogenous controls at global scales. Despite limitations in available data, we show that

cellulose decomposition can be an excellent proxy for litter decomposition, and our composite model of environmental drivers makes reliable estimates of litter decomposition at a global scale.

Forecasting decomposition under global environmental change

The high explanatory power of our cellulose and leaf-litter decomposition models enables forecasting of decomposition rates under altered climate, land cover, soil conditions, and nutrient-loading scenarios. These predictions can identify locations across the globe where decomposition may be particularly susceptible or resistant to global change, thereby informing freshwater-conservation efforts. As proof of concept, we examined potential changes in predicted litter-decomposition rates associated with changes in pine-oak forest composition in Mexican watersheds invaded by pine bark beetle (*Dendroctonus mexicanus*) (35). This invasion is expected to be particularly severe in the watershed of the Rio Grande de Santiago, a major conduit of organic matter to the Pacific Ocean in Mexico (Fig. 4). Our forecasts predict that insect-induced canopy replacement from pine to oak would cause decomposition rates to increase and become more variable (2.5- to 3.8-fold increase) with larger increases in decomposition associated with watersheds with greater evapotranspiration and drier soils (fig. s1). To promote the use of our models for forecasting, we created an easy-to-use, open-source online application where users can estimate both cotton-strip and leaf-litter decomposition rates for any river across the globe (<https://shiny-bsci.kent.edu/CELLDEX>).

Conclusions and implications

By pairing a distributed field experiment with publicly available environmental data, we created the first high-resolution map and predictions of organic-matter decomposition rates in flowing

waters worldwide. Our model demonstrates that cellulose-decomposition results from diverse, interacting, and non-linear environmental forcings that can best be described with complex, data-rich models. Although the standard cotton fabric used lacks the biochemical complexity of leaf litter, our relatively simple organic-matter substrate is an excellent proxy for leaf litter in decomposition studies, as demonstrated by our model predictions. Simplification of the leaf-litter-bag assay allowed us to both achieve standardized results and fill extensive geographic gaps in remote and low-resourced areas, demonstrating the power of coordinated, distributed experiments (36). Although our datasets were large when compared against other studies of organic-matter decomposition, the field data used were relatively limited in both space and time, which makes our strong explanatory power all the more striking. Thus, this work also underscores the power of machine-learning algorithms and large geographic databases of environmental data (e.g., HydroBASINS (37, 38)) plus the critical value of temporally and geographically extensive data from simple but standardized coordinated experiments (e.g., CELLDEX).

Given the pressing information needs of measuring ecosystem functions for biomonitoring and bioassessment (39, 40), our globally distributed experiment provides a template for matching observational data with model predictions. This approach provided baseline data for estimated decomposition rates across immense, unstudied areas of the planet, and supports the development of biomonitoring networks in areas where they are most needed (41). To further advance large-scale monitoring and assessment we have made these modelling approaches accessible through an open-source online mapping tool. Application of the models to current and

future environmental threats will enable scientists and natural-resource managers to forecast changes in the functioning of river networks at a planetary scale.

Cellulose decomposition is strongly influenced by multiple interacting environmental drivers that continue to be impacted by anthropogenic activities. Undoubtedly, climate change, increased
5 nutrient loading, intensified land-use modification, and changes in vegetation cover will continue to alter organic-matter processing in rivers and streams. Notably, key human-influenced drivers of cellulose decomposition – especially nutrient loading and temperature – are positively related to decomposition rates. A critical implication is that, in the presence of continued environmental
10 change, organic-matter decomposition rates will likely increase in rivers, resulting in declines in shorter-term carbon storage (42) and reductions in carbon transfer to longer-term storage compartments, such as reservoirs, floodplains, and oceans.

References

1. J. Cebrian, Patterns in the fate of production in plant communities. *American Naturalist* **154**, 449–468 (1999).
2. T. J. Battin, R. Lauerwald, E. S. Bernhardt, E. Bertuzzo, L. G. Gener, R. O. Hall, E. R. Hotchkiss, T. Maavara, T. M. Pavelsky, L. Ran, P. Raymond, J. A. Rosentreter, P. Regnier, River ecosystem metabolism and carbon biogeochemistry in a changing world. *Nature* **613**, 449–459 (2023).
3. M. E. McClain, E. W. Boyer, C. L. Dent, S. E. Gergel, N. B. Grimm, P. M. Groffman, S. C. Hart, J. W. Harvey, C. A. Johnston, E. Mayorga, W. H. McDowell, G. Pinay, Biogeochemical hot spots and hot moments at the interface of terrestrial and aquatic ecosystems. *Ecosystems* **6**, 301–312 (2003).
<https://doi.org/10.1007/s10021-003-0161-9>.
4. E. R. Hotchkiss, R. O. Hall, R. A. Sponseller, D. Butman, J. Klaminder, H. Laudon, M. Rosvall, J. Karlsson, Sources of and processes controlling CO₂ emissions change with the size of streams and rivers. *Nature Geosciences* **8**, 696–699 (2015).
5. G. H. Allen, T. M. Pavelsky, Global extent of rivers and streams. *Science* **361**, 585–588(2018).
6. P. Regnier, P. Friedlingstein, P. Ciais, F. T. Mackenzie, N. Gruber, I. A. Janssens, G. G. Laruelle, R. Lauerwald, S. Luysaert, A. J. Andersson, S. Arndt, C. Arnosti, A. V. Borges, A. W. Dale, A. Gallego-Sala, Y. Godd ris, N. Goossens, J. Hartmann, C. Heinze, T. Ilyina, F. Joos, D. E. Larowe, J. Leifeld, F. J. R. Meysman, G. Munhoven, P. A. Raymond, R. Spahni, P. Suntharalingam, M. Thullner, Anthropogenic perturbation of the carbon fluxes from land to ocean. *Nature Geosciences* **6**, 597–607 (2013).
7. A. Marx, J. Dusek, J. Jankovec, M. Sanda, T. Vogel, R. van Geldern, J. Hartmann, J. A. C. Barth, A review of CO₂ and associated carbon dynamics in headwater streams: A global perspective. *Reviews of Geophysics* **55**, 560–585 (2017).
8. P. A. Raymond, J. Hartmann, R. Lauerwald, S. Sobek, C. McDonald, M. Hoover, D. Butman, R. Striegl, E. Mayorga, C. Humborg, P. Kortelainen, H. D rr, M. Meybeck, P. Ciais, P. Guth, Global carbon dioxide emissions from inland waters. *Nature* **503**, 355–359 (2013).
9. V. Ferreira, A. C. Encalada, M. A. S. Graça, Effects of litter diversity on decomposition and biological colonization of submerged litter in temperate and tropical streams. *Freshwater Science* **31**, 945–962 (2012).
10. A. Bruder, M. H. Schindler, M. S. Moretti, M. O. Gessner, Litter decomposition in a temperate and a tropical stream: The effects of species mixing, litter quality and shredders. *Freshwater Biology* **59**, 438–449 (2014).
11. J. C. Marks, Revisiting the fates of dead leaves that fall into streams. *Annual Review of Ecology, Evolution, and Systematics* **50**, 547–568 (2019).
12. M. A. S. Graça, The role of invertebrates on leaf litter decomposition in streams - A review. *International Review of Hydrobiology: A Journal Covering all Aspects of Limnology and Marine Biology* **86**, 383–393 (2001).
13. T. V. Royer, G. W. Minshall, Controls on leaf processing in streams from spatial-scaling and hierarchical perspectives. *Journal of the North American Benthological Society* **22**, 352–358 (2003).
14. J. J. Follstad Shah, J. S. Kominoski, M. Ard n, W. K. Dodds, M. O. Gessner, N. A. Griffiths, C. P. Hawkins, S. L. Johnson, A. Lecerf, C. J. LeRoy, D. W. P. Manning, A. D. Rosemond, R. L. Sinsabaugh, C. M. Swan, J. R. Webster, L. H. Zeglin, Global synthesis of the temperature sensitivity of leaf litter breakdown in streams and rivers. *Global Change Biology* **23**, 3064–3075 (2017).
15. M. Zhang, X. Cheng, Q. Geng, Z. Shi, Y. Luo, X. Xu, Leaf litter traits predominantly control litter decomposition in streams worldwide. *Global Ecology and Biogeography* **28**, 1469–1486 (2019).
16. L. Boyero, R. G. Pearson, M. O. Gessner, L. A. Barmuta, V. Ferreira, M. A. S. Graça, D. Dudgeon, A. J. Boulton, M. Callisto, E. Chauvet, J. E. Helson, A. Bruder, R. J. Albari o, C. M. Yule, M. Arunachalam, J. N. Davies, R. Figueroa, A. S. Flecker, A. Ram rez, R. G. Death, T. Iwata, J. M. Mathooko, C. Mathuriau, J. F. Gonalves, M. S. Moretti, T. Jinggut, S. Lamothe, C. M’Erimba, L. Ratnarajah, M. H. Schindler, J. Castela, L. M. Buria, A. Cornejo, V. D. Villanueva, D. C. West, A global experiment suggests climate warming will not accelerate litter decomposition in streams but might reduce carbon sequestration. *Ecology Letters* **14**, 289–294 (2011).
17. G. Woodward, M. O. Gessner, P. S. Giller, V. Gulis, S. Hladyz, A. Lecerf, B. Malmqvist, B. G. McKie, S. D. Tiegs, H. Cariss, M. Dobson, A. Eloegi, V. Ferreira, M. A. S. Graça, T. Fleituch, J. O. Lacoursi re, M. Nistorescu, J. Pozo, G. Risnoveanu, M. Schindler, A. Vadineanu, L. B.-M. Vought, E. Chauvet, Continental-scale effects of nutrient pollution on stream ecosystem functioning. *Science* **336**, 1438–1440 (2012).

18. I. T. Handa, R. Aerts, F. Berendse, M. P. Berg, A. Bruder, O. Butenschoen, E. Chauvet, M. O. Gessner, J. Jabiol, M. Makkonen, B. G. McKie, B. Malmqvist, E. T. H. M. Peeters, S. Scheu, B. Schmid, J. Van Ruijven, V. C. A. Vos, S. Hättenschwiler, Consequences of biodiversity loss for litter decomposition across biomes. *Nature* **509**, 218–221 (2014).
- 5 19. S. D. Tiegs, D. M. Costello, M. W. Isken, G. Woodward, P. B. McIntyre, M. O. Gessner, E. Chauvet, N. A. Griffiths, A. S. Flecker, V. Acuña, R. Albariño, D. C. Allen, C. Alonso, P. Andino, C. Arango, J. Aroviita, M. V. M. Barbosa, L. A. Barmuta, C. V. Baxter, T. D. C. Bell, B. Bellinger, L. Boyero, L. E. Brown, A. Bruder, D. A. Bruesewitz, F. J. Burdon, M. Callisto, C. Canhoto, K. A. Capps, M. M. Castillo, J. Clapcott, F. Colas, C. Colón-Gaud, J. Cornut, V. Crespo-Pérez, W. F. Cross, J. M. Culp, M. Danger, O. Dangles, E. De Eyto, A. M. Derry, V. D. Villanueva, M. M. Douglas, A. Elosegí, A. C. Encalada, S. Entekin, R. Espinosa, D. Ethaiya, V. Ferreira, C. Ferriol, K. M. Flanagan, T. Fleituch, J. J. F. Shah, A. F. Barbosa, N. Friberg, P. C. Frost, E. A. Garcia, L. G. Lago, P. E. G. Soto, S. Ghate, D. P. Giling, A. Gilmer, J. F. Gonçalves, R. K. Gonzales, M. A. S. Graça, M. Grace, H.-P. Grossart, F. Guérol, V. Gulis, L. U. Hepp, S. Higgins, T. Hishi, J. Huddart, J. Hudson, S. Imberger, C. Iñiguez-Armijos, T. Iwata, D. J. Janetski, E. Jennings, A. E. Kirkwood, A. A. Koning, S. Kosten, K. A. Kuehn, H. Laudon, P. R. Leavitt, A. L. L. Da Silva, S. J. Leroux, C. J. LeRoy, P. J. Lisi, R. MacKenzie, A. M. Marcarelli, F. O. Masese, B. G. McKie, A. O. Medeiros, K. Meissner, M. Miliša, S. Mishra, Y. Miyake, A. Moerke, S. Mombrikotb, R. Mooney, T. Moulton, T. Muotka, J. N. Negishi, V. Neres-Lima, M. L. Nieminen, J. Nimptsch, J. Ondruch, R. Paavola, I. Pardo, C. J. Patrick, E. T. H. M. Peeters, J. Pozo, C. Pringle, A. Prussian, E. Quenta, A. Quesada, B. Reid, J. S. Richardson, A. Rigosi, J. Rincón, G. Rišnoveanu, C. T. Robinson, L. Rodríguez-Gallego, T. V. Royer, J. A. Rusak, A. C. Santamans, G. B. Selmečzy, G. Simiyu, A. Skuja, J. Smykla, K. R. Sridhar, R. Sponseller, A. Stoler, C. M. Swan, D. Szlag, F. Teixeira-De Mello, J. D. Tonkin, S. Uusheimo, A. M. Veach, S. Vilbaste, L. B. M. Vought, C.-P. Wang, J. R. Webster, P. B. Wilson, S. Woelfl, M. A. Xenopoulos, A. G. Yates, C. Yoshimura, C. M. Yule, Y. X. Zhang, J. A. Zwart, Global patterns and drivers of ecosystem functioning in rivers and riparian zones. *Sci Adv* **5**, eaav0486 (2019).
- 25 20. D. M. Costello, S. D. Tiegs, L. Boyero, C. Canhoto, K. A. Capps, M. Danger, P. C. Frost, M. O. Gessner, N. A. Griffiths, H. M. Halvorson, K. A. Kuehn, A. M. Marcarelli, T. V. Royer, D. M. Mathie, R. J. Albariño, C. P. Arango, J. Aroviita, C. V. Baxter, B. J. Bellinger, A. Bruder, F. J. Burdon, M. Callisto, A. Camacho, F. Colas, J. Cornut, V. Crespo-Pérez, W. F. Cross, A. M. Derry, M. M. Douglas, A. Elosegí, E. de Eyto, V. Ferreira, C. Ferriol, T. Fleituch, J. J. Follstad Shah, A. Frainer, E. A. Garcia, L. García, P. E. García, D. P. Giling, R. K. Gonzales-Pomar, M. A. S. Graça, H.-P. Grossart, F. Guérol, L. U. Hepp, S. N. Higgins, T. Hishi, C. Iñiguez-Armijos, T. Iwata, A. E. Kirkwood, A. A. Koning, S. Kosten, H. Laudon, P. R. Leavitt, A. L. Lemes da Silva, S. J. Leroux, C. J. LeRoy, P. J. Lisi, F. O. Masese, P. B. McIntyre, B. G. McKie, A. O. Medeiros, M. Miliša, Y. Miyake, R. J. Mooney, T. Muotka, J. Nimptsch, R. Paavola, I. Pardo, I. Y. Parnikoza, C. J. Patrick, E. T. H. M. Peeters, J. Pozo, B. Reid, J. S. Richardson, J. Rincón, G. Rišnoveanu, C. T. Robinson, A. C. Santamans, G. M. Simiyu, A. Skuja, J. Smykla, R. A. Sponseller, F. Teixeira-de Mello, S. Vilbaste, V. D. Villanueva, J. R. Webster, S. Woelfl, M. A. Xenopoulos, A. G. Yates, C. M. Yule, Y. Zhang, J. A. Zwart, Global patterns and controls of nutrient immobilization on decomposing cellulose in riverine ecosystems. *Global Biogeochemical Cycles* **36**, e2021GB007163 (2022).
- 40 21. C. M. Gough, Terrestrial primary production: Fuel for life. *Nature Education Knowledge* **3**, 28 (2011).
22. C. B. Field, M. J. Behrenfeld, J. T. Randerson, P. Falkowski, Primary production of the biosphere: Integrating terrestrial and oceanic components. *Science* **281**, 237–240 (1998).
23. T. H. Huang, Y. H. Fu, P. Y. Pan, C. T. A. Chen, Fluvial carbon fluxes in tropical rivers. *Current Opinion in Environmental Sustainability* **4**, 162–169 (2012).
- 45 24. S. D. Tiegs, J. E. Clapcott, N. A. Griffiths, A. J. Boulton, A standardized cotton-strip assay for measuring organic-matter decomposition in streams. *Ecological Indicators* **32**, 131–139 (2013).
25. J. Mancuso, J. L. Tank, U. H. Mahl, A. Vincent, S. D. Tiegs, Monthly variation in organic-matter decomposition in agricultural stream and riparian ecosystems. *Aquatic Sciences* **85**, 83 (2023).
- 50 26. M. Ardón, L. H. Zeglin, R. M. Utz, S. D. Cooper, W. K. Dodds, R. J. Bixby, A. S. Burdett, J. Follstad Shah, N. A. Griffiths, T. K. Harms, S. L. Johnson, J. B. Jones, J. S. Kominoski, W. H. McDowell, A. D. Rosemond, M. T. Trentman, D. Van Horn, A. Ward, Experimental nitrogen and phosphorus enrichment stimulates multiple trophic levels of algal and detrital-based food webs: A global meta-analysis from streams and rivers. *Biological Reviews* **96**, 692–715 (2021).

27. C. J. LeRoy, A. L. Hipp, K. Lueders, J. J. Follstad Shah, J. S. Kominoski, M. Ardón, W. K. Dodds, M. O. Gessner, N. A. Griffiths, A. Lecerf, D. W. P. Manning, R. L. Sinsabaugh, J. R. Webster, Plant phylogenetic history explains in-stream decomposition at a global scale. *Journal of Ecology* **108**, 17–35 (2020).
28. K. Yue, P. De Frenne, K. Van Meerbeek, V. Ferreira, D. A. Fornara, Q. Wu, X. Ni, Y. Peng, D. Wang, P. Heděnc, Y. Yang, F. Wu, J. Peñuelas, Litter quality and stream physicochemical properties drive global invertebrate effects on instream litter decomposition. *Biological Reviews* **97**, 2023–2038 (2022).
29. A. D. Rosemond, C. M. Pringle, A. Ramírez, M. J. Paul, J. L. Meyer, Landscape variation in phosphorus concentration and effects on detritus-based tropical streams. *Limnology and Oceanography* **47**, 278–289 (2002).
30. L. Boyero, M. A. S. Graça, A. M. Tonin, J. Pérez, A. J. Swafford, V. Ferreira, A. Landeira-Dabarca, M. A. Alexandrou, M. O. Gessner, B. G. McKie, R. J. Albariño, L. A. Barmuta, M. Callisto, J. Chará, E. Chauvet, C. Colón-Gaud, D. Dudgeon, A. C. Encalada, R. Figueroa, A. S. Flecker, T. Fleituch, A. Frainer, J. F. Gonçalves, J. E. Helson, T. Iwata, J. Mathooko, C. M’Erimba, C. M. Pringle, A. Ramírez, C. M. Swan, C. M. Yule, R. G. Pearson, Riparian plant litter quality increases with latitude. *Scientific Reports* **7**, 10562 (2017).
31. J. Kattge, S. Díaz, S. Lavorel, I. C. Prentice, P. Leadley, G. Bönisch, E. Garnier, M. Westoby, P. B. Reich, I. J. Wright, J. H. C. Cornelissen, C. Violle, S. P. Harrison, P. M. Van Bodegom, M. Reichstein, B. J. Enquist, N. A. Soudzilovskaia, D. D. Ackerly, M. Anand, O. Atkin, M. Bahn, T. R. Baker, D. Baldocchi, R. Bekker, C. C. Blanco, B. Blonder, W. J. Bond, R. Bradstock, D. E. Bunker, F. Casanoves, J. Cavender-Bares, J. Q. Chambers, F. S. Chapin, J. Chave, D. Coomes, W. K. Cornwell, J. M. Craine, B. H. Dobrin, L. Duarte, W. Durka, J. Elser, G. Esser, M. Estiarte, W. F. Fagan, J. Fang, F. Fernández-Méndez, A. Fidelis, B. Finegan, O. Flores, H. Ford, D. Frank, G. T. Freschet, N. M. Fyllas, R. V. Gallagher, W. A. Green, A. G. Gutierrez, T. Hickler, S. I. Higgins, J. G. Hodgson, A. Jalili, S. Jansen, C. A. Joly, A. J. Kerkhoff, D. Kirkup, K. Kitajima, M. Kleyer, S. Klotz, J. M. H. Knops, K. Kramer, I. Kühn, H. Kurokawa, D. Laughlin, T. D. Lee, M. Leishman, F. Lens, T. Lenz, S. L. Lewis, J. Lloyd, J. Llusà, F. Louault, S. Ma, M. D. Mahecha, P. Manning, T. Massad, B. E. Medlyn, J. Messier, A. T. Moles, S. C. Müller, K. Nadrowski, S. Naeem, Ü. Niinemets, S. Nöllert, A. Nüske, R. Ogaya, J. Oleksyn, V. G. Onipchenko, Y. Onoda, J. Ordoñez, G. Overbeck, W. A. Ozinga, S. Patiño, S. Paula, J. G. Pausas, J. Peñuelas, O. L. Phillips, V. Pillar, H. Poorter, L. Poorter, P. Poschlod, A. Prinzing, R. Proulx, A. Rammig, S. Reinsch, B. Reu, L. Sack, B. Salgado-Negret, J. Sardans, S. Shiodera, B. Shipley, A. Siefert, E. Sosinski, J. F. Soussana, E. Swaine, N. Swenson, K. Thompson, P. Thornton, M. Waldram, E. Weiher, M. White, S. White, S. J. Wright, B. Yguel, S. Zaehle, A. E. Zanne, C. Wirth, TRY - A global database of plant traits. *Global Change Biology* **17**, 2905–2935 (2011).
32. C. J. LeRoy, T. G. Whitham, S. C. Wooley, J. C. Marks, Within-species variation in foliar chemistry influences leaf-litter decomposition in a Utah river. *Journal of the North American Benthological Society* **26**, 426–438 (2007).
33. A. Lecerf, E. Chauvet, Intraspecific variability in leaf traits strongly affects alder leaf decomposition in a stream. *Basic and Applied Ecology* **9**, 598–605 (2008).
34. T. Sariyildiz, J. M. Anderson, Decomposition of sun and shade leaves from three deciduous tree species, as affected by their chemical composition. *Biology and Fertility of Soils* **37**, 137–146 (2003).
35. A. González-Hernández, R. Morales-Villafaña, M. E. Romero-Sánchez, B. Islas-Trejo, R. Pérez-Miranda. Modelling potential distribution of a pine bark beetle in Mexican temperate forests using forecast data and spatial analysis tools. *J For Res*, **31**, 649–659 (2020).
36. L. H. Fraser, H. Al Henry, C. N. Carlyle, S. R. White, C. Beierkuhnlein, J. F. Cahill, B. B. Casper, E. Cleland, S. L. Collins, J. S. Dukes, A. K. Knapp, E. Lind, R. Long, Y. Luo, P. B. Reich, M. D. Smith, M. Sternberg, R. Turkington, Coordinated distributed experiments: An emerging tool for testing global hypotheses in ecology and environmental science. *Frontiers in Ecology and the Environment* **11**, 147–155 (2013).
37. B. Lehner, K. Verdin, A. Jarvis, New global hydrography derived from spaceborne elevation data. *Eos, Transactions American Geophysical Union* **89**, 93–94 (2008).
38. B. Lehner, G. Grill, Global river hydrography and network routing: Baseline data and new approaches to study the world’s large river systems. *Hydrological Processes* **27**, 2171–2186 (2013).
39. M. O. Gessner, E. Chauvet, A case for using litter breakdown to assess functional stream integrity. *Ecological Applications* **12**, 498–510 (2002).

40. M. C. Jackson, O. L. F. Weyl, F. Altermatt, I. Durance, N. Friberg, A. J. Dumbrell, J. J. Piggott, S. D. Tiegs, K. Tockner, C. B. Krug, P. W. Leadley, G. Woodward, Recommendations for the next generation of global freshwater biological monitoring tools. *Advances in Ecological Research* **55**, 615–636 (2016).
- 5 41. K. A. Wilson, N. A. Auerbach, K. Sam, A. G. Magini, A. S. L. Moss, S. D. Langhans, S. Budiharta, D. Terzano, E. Meijaard, Conservation research is not happening where it is most needed. *PLoS Biology* **14**, e1002413 (2016).
42. A. D. Rosemond, J. P. Benstead, P. M. Bumpers, V. Gulis, J. S. Kominoski, D. W. P. Manning, K. Suberkropp, J. B. Wallace, Experimental nutrient additions accelerate terrestrial carbon loss from stream ecosystems. *Science* **347**, 1142–1145 (2015).
- 10 43. D. Costello, J. P. Schmidt, C. Patrick, K. Capps, J. Follstad Shah, C. LeRoy, and S.D. Tiegs. Data from: Human activities shape global patterns of decomposition rates in rivers, Zenodo (2024); <https://zenodo.org/doi/10.5281/zenodo.10688947>
44. J. Cheng, B. Schloerke, B. Karambelkar, Y. Xie, leaflet: Create Interactive Web Maps with the JavaScript “Leaflet” Library, version 2.2.1, Comprehensive R Archive Network (2023); <https://cran.r-project.org/package=leaflet>
- 15 45. A. N. Strahler, Quantitative analysis of watershed geomorphology. *Eos, Transactions American Geophysical Union* **38**, 913–920 (1957).
46. R. W. McDowell, A. Noble, P. Pletnyakov, L. M. Mosley, Global database of diffuse riverine nitrogen and phosphorus loads and yields. *Geoscience Data Journal* **8**, 132–143 (2021).
- 20 47. D. Ackerman, D. B. Millet, X. Chen, Global estimates of inorganic nitrogen deposition across four decades. *Global Biogeochemical Cycles* **33**, 100–107 (2019).
48. J. Brahney, N. Mahowald, D. S. Ward, A. P. Ballantyne, J. C. Neff, Is atmospheric phosphorus pollution altering global alpine Lake stoichiometry? *Global Biogeochemical Cycles* **29**, 1369–1383 (2015).
- 25 49. N. Mahowald, T. D. Jickells, A. R. Baker, P. Artaxo, C. R. Benitez-Nelson, G. Bergametti, T. C. Bond, Y. Chen, D. D. Cohen, B. Herut, N. Kubilay, R. Losno, C. Luo, W. Maenhaut, K. A. McGee, G. S. Okin, R. L. Siefert, S. Tsukuda, Global distribution of atmospheric phosphorus sources, concentrations and deposition rates, and anthropogenic impacts. *Global Biogeochemical Cycles* **22**, GB4026 (2008).
50. J. Elith, J. R. Leathwick, T. Hastie, A working guide to boosted regression trees. *Journal of Animal Ecology* **77**, 802–813 (2008).
- 30 51. R Core Team. R: A language and environment for statistical computing, version 4.3.2. Comprehensive R Archive Network (2023); <https://www.R-project.org/>
52. G. Ridgeway, GBM Developers. gbm: Generalized boosted regression models, version 2.1.9, Comprehensive R Archive Network (2024); <https://cran.r-project.org/package=gbm>
53. L. Breiman, Random forests. *Machine Learning* **45**, 5–32 (2001).
- 35 54. A. M. Thorn, J. R. Thompson, J. S. Plisinski, Patterns and predictors of recent forest conversion in New England. *Land* **5**, 30 (2016).
55. R. J. Hijmans, raster: Geographic data analysis and modeling, version 3.6-36, Comprehensive R Archive Network (2023); <https://cran.r-project.org/package=raster>

40 **Acknowledgments:** We are grateful for the efforts of the many people who assisted with the CELLDEX project in the lab and in the field, for Jasmine Mancuso for edits on an earlier version of this manuscript, Diane Ethaiya for logistical assistance during the CELLDEX project, and Joshua Talbott for assistance with the Shiny application. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

45 **Funding:** This work was sponsored by an Ecuadorian National Science Foundation PROMETEO award to ST. Original data compilation of leaf litter decomposition rates from primary literature was supported by a working group grant to JFS from the U.S. National Science Foundation (Division of Environmental Biology #1545288 and #1929393) through the U.S. Long Term Ecological Research Network. A portion of the salary of KAC was supported by the

50

Department of Energy Office of Environmental Management under Award Number DE-EM0005228 to the University of Georgia Research Foundation.

Author contributions:

Conceptualization: DC, JPS, KC, ST

5 Methodology: CP, DC, JPS, KC, ST

Investigation: All co-authors. CL and JFS also provided data from a literature review

Visualization: DC, JPS

Funding acquisition: ST

Writing – original draft: KC, ST

10 Writing – review and editing: BM, CP, DC, FB, JPS, KC, MG, NG, ST, GW

Competing interests/Disclaimer: Authors declare that they have no competing interests.

15 **Data and materials availability:** All data and code for analyses and figures are available on GitHub (43).

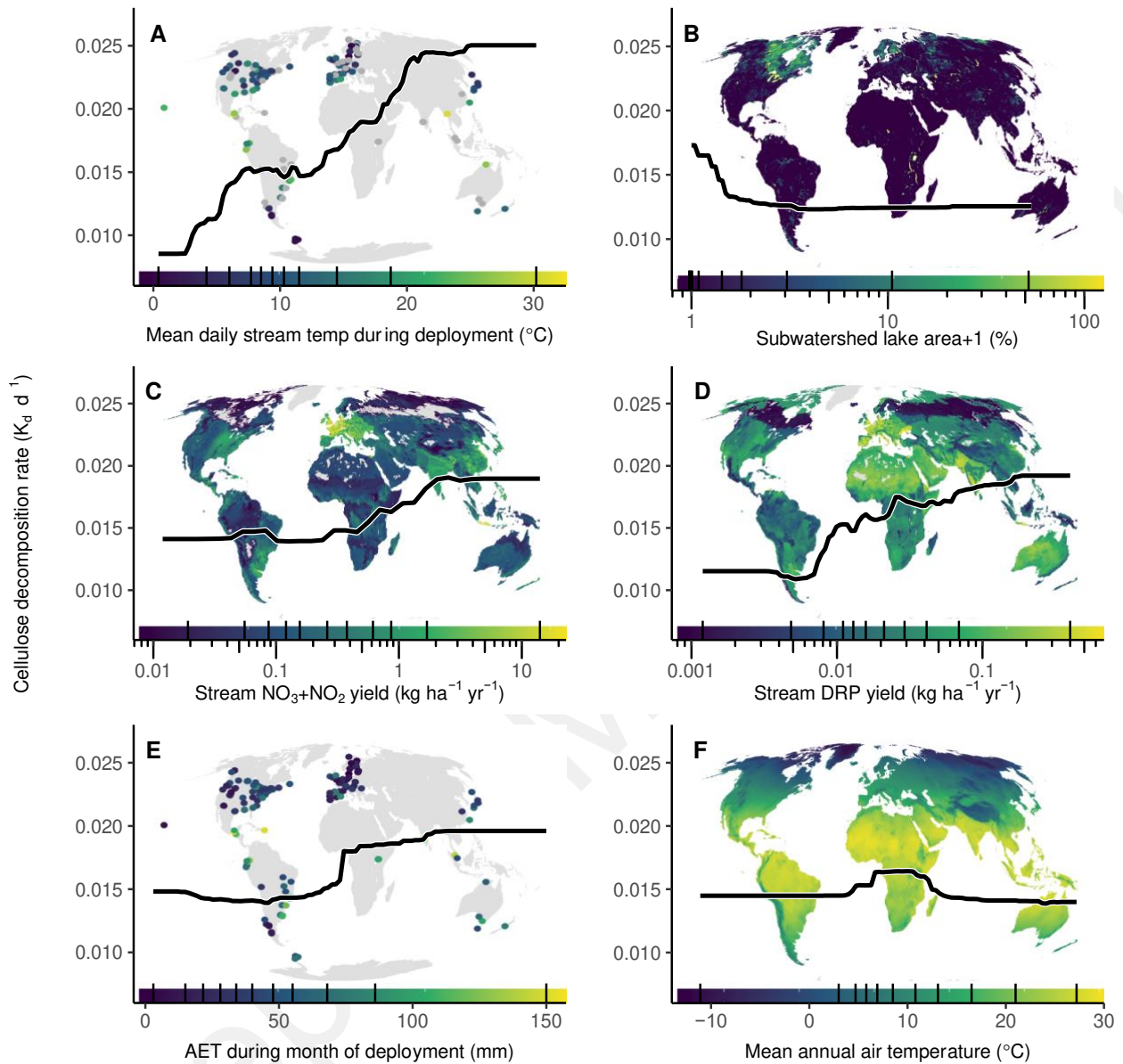


Fig. 1. Partial-dependence plots (black lines) of the top variables that explain and predict cellulose-decomposition rates (K_d). Background maps show global distributions of explanatory variables in Mollweide projection. The boosted-regression tree model explains 81% of the variance in decomposition rates across the 514 streams used in our study. Most top variables relate to climate and water quality and effects exhibit non-linear threshold responses. Black ticks above the x-axis indicate decile breaks.

5

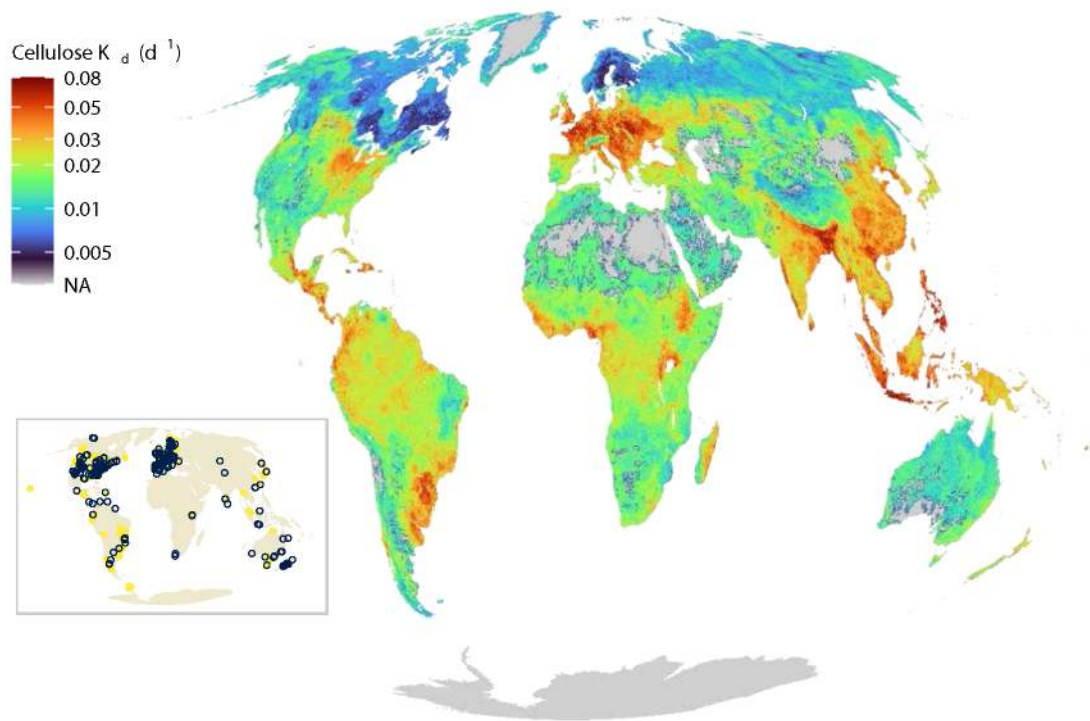


Fig. 2. Predicted mean annual cellulose-decomposition rates (K_d) revealing broad spatial patterns in decomposition rates. We did not predict K_d for sub-watersheds with ≤ 10 ha of sub-basin area, nor for Antarctica, for which we did not have values for most predictor variables. Inset shows study sites for cellulose (light-filled circles) and leaf-litter (dark-filled circles) decomposition measurements. Map and inset are Mollweide projection.

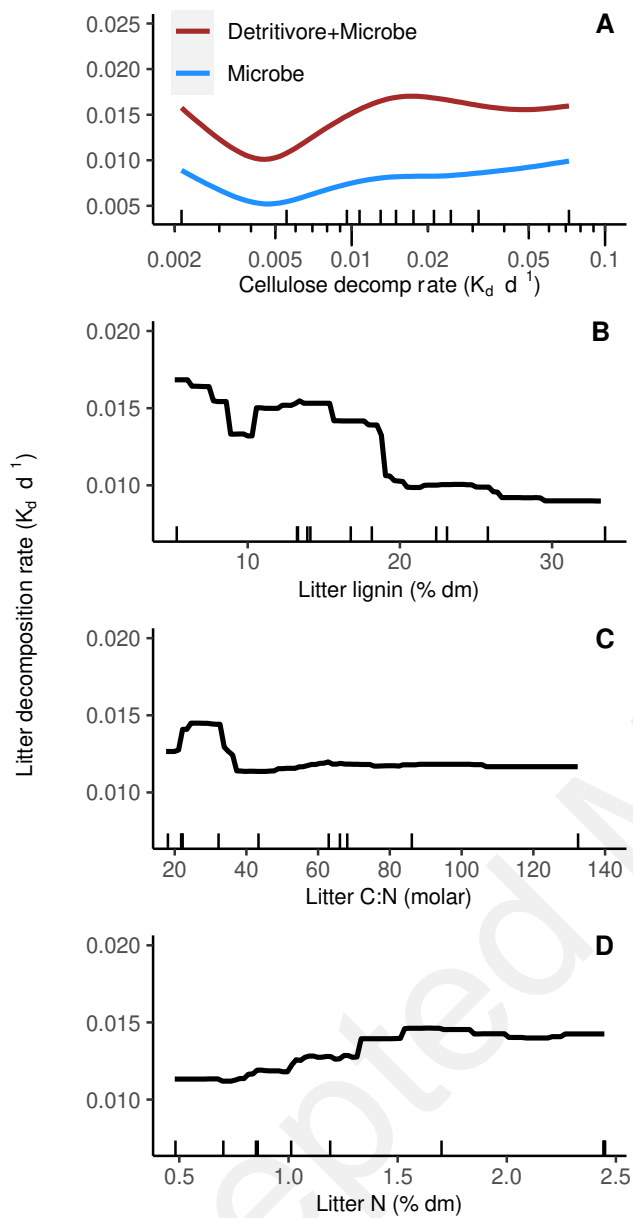


Fig. 3. Partial-dependence plots of the top variables that explain leaf-litter-decomposition rates (K_d). The boosted-regression-tree model explains 70% of the variance in rates across 895 published values of leaf-litter decomposition and leaf quality (27). Top explanatory variables included our modeled cellulose-decomposition rates, invertebrate access to the leaf material, and attributes related to litter quality. Smooth fits (GAM) show the relationship between cellulose-decomposition rate and litter decomposition for the two different common litter-bag mesh sizes that allow or exclude invertebrates (A). The smooth fits capture the general environmental effects on decomposition, whereas the partial dependency plots (thin lines) are noisier due to covariation in leaf quality and environmental conditions (i.e., certain leaf types are used in certain regions). Black ticks above x -axis indicate decile breaks. Note the change in y -axis between panel A and B-C.

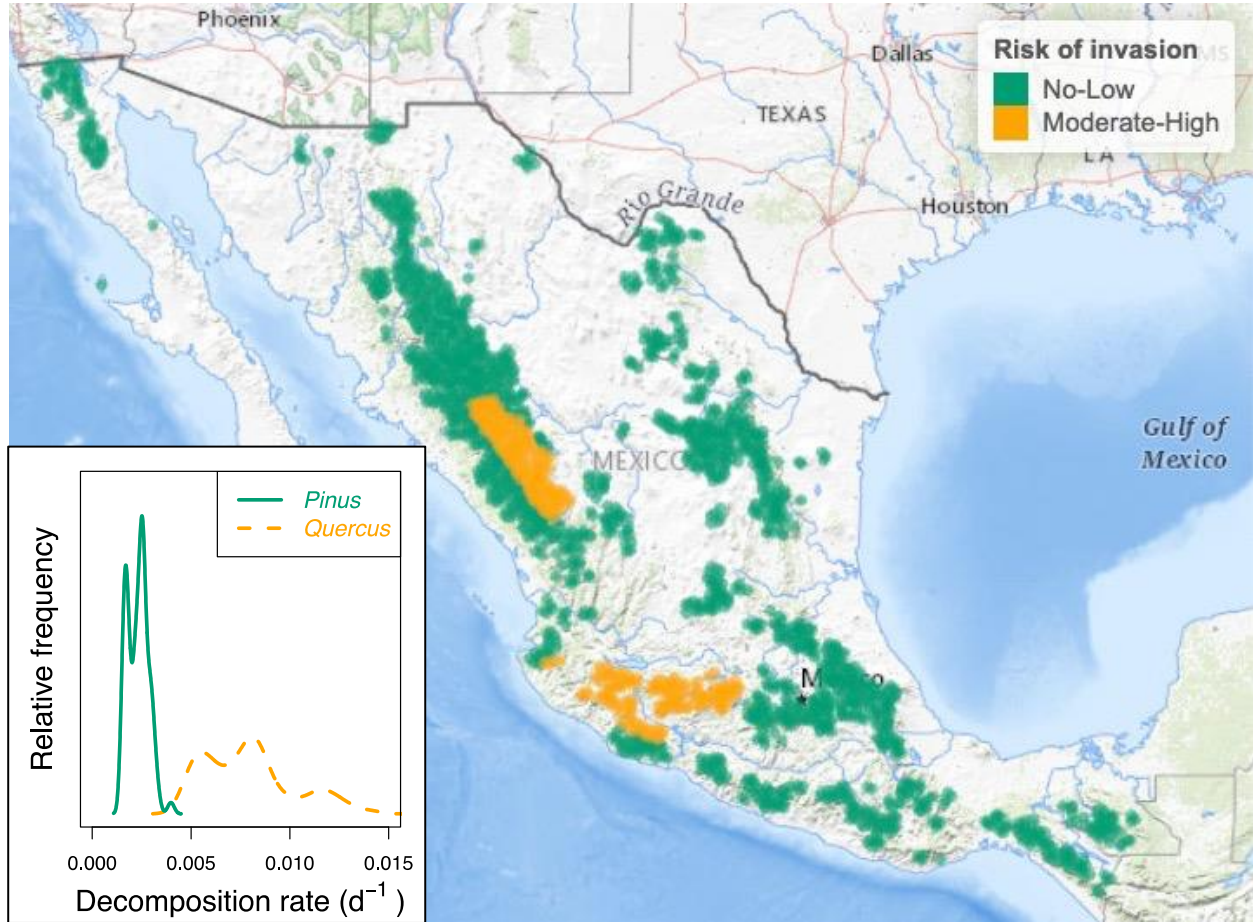


Fig. 4. Distribution of temperate-coniferous forests in Mexico (all points) and locations (orange) where there is a moderate-to-high risk of pine bark beetle (*Dendroctonus mexicanus*) invasion (adapted from (35)) that drives a shift from coniferous to deciduous forest. Inset shows the density distribution of predicted litter-decomposition rates for streams in areas of moderate-to-high invasion risk both for pine litter (green solid line) and oak litter (orange dashed line). Our model predicts that full canopy replacement from pine to oak would increase leaf-litter decomposition rates 2.5- to 3.8-fold with a greater increase predicted in watersheds with greater evapotranspiration and drier soils. Base from U.S. Geological Survey, The National Map, 2023; Web Mercator projection; created in the R package leaflet 2.2.1 (44).

List of Supplemental Materials (SM):

- 15 CELLDEX Consortium Authors and Affiliations
- Materials and Methods
- Figure S1
- Tables S1 and S2
- References 45–55

20