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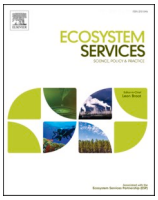

Beyond the thermometer: Responsible interpretation of vegetation-climate modelling requires an ecosystem-service perspective

Theodore A. Endreny [a,*], TC Chakraborty [b], Javier Diez-Sierra [c], Manuel Esperon-Rodriguez [d], Rüdiger Grote [e], Christopher Claus Holst [e], Rob McDonald [f], Philipp Porada [g], Nadine Ruehr [e], Chenghao Wang [h]

[a] Department of Environmental Resources Engineering, State University of New York College of Environmental Science and Forestry (SUNY ESF), Syracuse, NY, USA
[b] Earth System Modeling Group, Pacific Northwest National Laboratory (PNNL), WA, USA
[c] Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
[d] School of Environmental & Natural Sciences, College of Environmental Sciences and Engineering, Bangor University, Bangor, LL57 2DG, UK
[e] Institute of Meteorology and Climate Research – Atmospheric Environmental Research (IMK-IFU), Karlsruhe Institute of Technology (KIT), Garmisch-Partenkirchen, Germany
[f] The Nature Conservancy, Berlin, Germany; CUNY Institute for Demographic Research, New York, NY, USA; Humboldt University, Berlin, Germany
[g] Institute of Plant Sciences and Microbiology, University of Hamburg, Hamburg, Germany
[h] School of Meteorology and Department of Geography and Environmental Sustainability, University of Oklahoma, Norman, OK, USA

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ABSTRACT

Changes in vegetation structure, composition, and distribution are among the most consequential drivers of land–atmosphere interactions and associated ecosystem services. Vegetation–climate modelling frameworks often rely on temperature-based indicators, most commonly near-surface temperature, and in some cases land surface temperature, as primary outcome metrics. This commentary argues that many policy interpretations extend beyond the scope of typical vegetation–climate modelling frameworks by treating temperature responses as comprehensive indicators of climate effectiveness or broader ecosystem-service outcomes, thereby risking maladaptive policy decisions. We emphasize that these concerns do not undermine the scientific value of these modelling studies. Rather, they highlight the pressing need to interpret model outputs as conditional diagnostics that should be considered alongside broader ecosystem-service tradeoffs, ecological feedbacks, and human impacts.

1. Introduction

Changes in vegetation structure, composition, and distribution are among the most consequential drivers of land–atmosphere interactions and associated ecosystem services (Smith et al., 2017). These changes influence the surface energy balance, hydrological processes, carbon storage, climate regulation, biodiversity, and ecosystem functioning across spatial and temporal scales (Ehbrecht et al., 2021; Foley et al., 2005). Given the importance of vegetation, many climate impact studies have examined the biophysical effects of vegetation change on near-surface climate, often using idealized or scenario-based simulations to isolate specific mechanisms. Such studies have yielded valuable insights into how vegetation modulates surface temperature, turbulent heat fluxes, and radiative exchange under controlled conditions.

Vegetation–climate modelling frameworks often focus on temperature-based indicators, most commonly near-surface temperature and in some cases land surface temperature, as primary outcome metrics. Resulting temperature responses are often discussed in terms of vegetation-driven "cooling" or "warming" and are increasingly interpreted as indicators of climate effectiveness or heat mitigation potential (Alkama and Cescatti, 2016; Arora and Montenegro, 2011; Devaraju et al., 2018; Yao et al., 2025). This narrow scoping reflects a deliberate and scientifically justified modelling choice that enables clearer attribution of underlying mechanisms, facilitates comparison across experiments, and maintains computational tractability. Challenges arise, however, when outputs from these modelling studies are interpreted beyond their original design intent, treating a single modelled service as representative of vegetation's full ecosystem service portfolio.

* Corresponding author.
E-mail address: te@esf.edu (T.A. Endreny).

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In such cases, temperature responses, which is one service among the many that vegetation regulates, may be interpreted as indicators of broader climate or human impacts that fall outside the intended scope of the underlying model structure.

This commentary argues that extrapolative interpretations of vegetation-climate modelling studies, especially in general-interest journals, exceed the intended scope of their original modelling frameworks. Illustrative of this concern, studies such as Yao et al. (2025), titled *"Conversion from coniferous to broadleaved trees can make European forests more climate-effective,"* may be interpreted as supporting vegetation conversion strategies based primarily on modelled reductions in air temperature associated with increased surface albedo, despite broader ecosystem feedbacks, climate interactions, and human thermal responses remaining outside the intended scope of the modelling framework. Such interpretations risk policy mistakes that degrade ecosystem functioning or contribute to climate maladaptation. We emphasize that these concerns do not undermine the scientific value of these modelling studies, which remain essential tools for understanding specific land–atmosphere interactions and constrained ecosystem responses to climate forcings. Rather, they highlight the need for careful and holistic interpretation of model outputs as conditional diagnostics rather than comprehensive measures of climate effectiveness or broader ecosystem services.

1.1. Temperature responses capture only a subset of vegetation–climate interactions

Terrestrial vegetation mediates the Earth's climate through an intricate combination of biogeophysical and biogeochemical processes that extend far beyond near-surface air temperature regulation. Changes in vegetation structure, composition, and distribution influence carbon and water fluxes, humidity, atmospheric circulation, ecosystem resilience, and a wide range of ecological services, operating across scales from local microclimates to global feedbacks (Ehbrecht et al., 2021). Of note, vegetation influences surface climate not only through albedo modification and shading, but also through evapotranspiration, carbon sequestration, hydrology, phenology, effects on disturbance regimes and atmospheric composition, and other interacting and nonlinear pathways. Crucially, vegetation provides a suite of climate-regulating ecosystem services, such as the direct modulation of cloud cover and the biological triggering of seasonal precipitation (Wright et al., 2017). Many of these processes interact nonlinearly and operate across scales that extend beyond the spatial and temporal resolution of most regional and global climate models.

In comparison, vegetation–climate modelling studies often intentionally focus on a subset of these complex processes, most commonly biophysical effects on temperature. While such an approach is well suited for isolating specific mechanisms and appropriate to the capabilities of these modelling frameworks, temperature responses alone cannot represent the net climatic consequences of vegetation change (Fig. 1). Prior studies have emphasized that regional temperature responses diverge in sign, magnitude, and relevance from net climate outcomes when carbon storage, ecosystem resilience, land–atmosphere feedbacks, and atmospheric chemistry are collectively considered (Amali et al., 2025). Therefore, simulated surface and near–surface cooling or warming should not be interpreted as synonymous with climate mitigation or climate damage. Instead, these responses represent one component of many modulated by model structure and data availability. Interpreting temperature responses in isolation risks conflating mechanistic diagnostics with integrated climate effectiveness, particularly when such results are communicated to audiences outside a narrow modelling community to guide policy decisions and resource allocations for mitigation and adaptation purposes. Evidence that trees mitigate a single environmental hazard within a narrowly scoped study does not automatically justify broader implementation without considering competing pathways and trade-offs.

1.2. Models simplify many biogeochemical processes relevant for climate policy

Vegetation–climate models necessarily simplify many processes that influence surface energy exchange and thermal stress. Species–level differences in albedo, canopy architecture, water use strategies, phenology, volatile organic compound emissions, and senescence sensitivity to drought stress are typically underrepresented, using prescribed general responses, aggregated functional types, or are even completely neglected. These simplifications are appropriate for many research questions but condition the meaning of simulated responses (Li et al., 2023). For example, relationships inferred from time–averaged conditions may not hold during extreme heat and drought events,

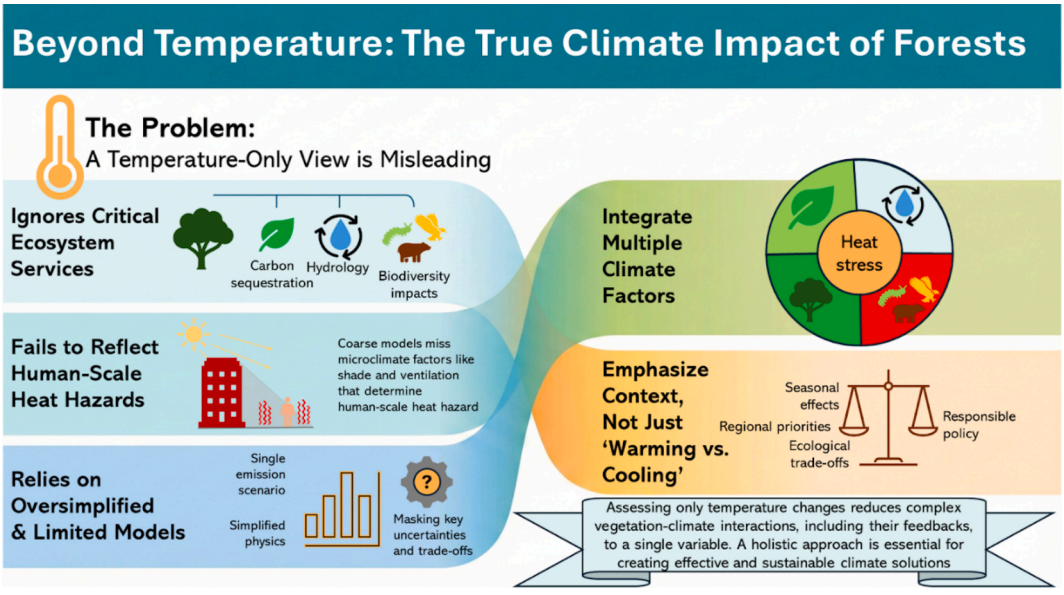

Fig. 1. Conceptual framing of challenges that arise when narrowly scoped model outputs, such as temperature responses, are interpreted as comprehensive indicators of vegetation–climate impacts. The figure highlights how single-metric interpretations may overlook broader ecosystem services, ecological feedbacks, and human-scale processes, emphasizing the need to interpret modelled responses within their modelling and climate context.

leading modelled plant functional responses to diverge from those of real vegetation as physiological constraints intensify from stomatal closure to forest decline (Choat et al., 2018). These responses can substantially alter water, carbon, and energy exchange, with important implications for evapotranspiration and surface cooling.

Several vegetation–climate modelling approaches parameterize species responses using long–term climate averages, whereas tree growth, stress, and mortality are often governed by short–term weather extremes rather than climatic means. Heatwaves, droughts, and frost events can drive physiological thresholds and mortality risk more strongly than annual averages, thus resulting in shifts in vegetation composition not captured by models (Choat et al., 2018). Reliance on mean climate conditions may therefore obscure sensitivity to extreme–event dynamics, reinforcing the need to interpret modelled responses as conditional on both temporal resolution and process sensitivity.

Temperature responses may indicate surface albedo contrasts following conversion from forests to higher–albedo grasslands. However, observational evidence indicates that such cooling is largely confined to higher northern latitudes (Lee et al., 2021) and may reverse over decadal time scales as carbon–cycle feedbacks accumulate (Williams et al., 2021). These findings highlight that albedo–induced cooling is both geographically and temporally contingent, and in some cases dependent on large–scale feedbacks that may not operate under local land–use changes. This contrasts with emergent outcomes of fully coupled vegetation–atmosphere–human interactions (Yao et al., 2025). The structural simplifications applied in this example can lend simulations an appearance of precision while masking key sources of uncertainty, increasing the risk that results are interpreted as robust or transferable beyond the modelled context. Properly framing this conditionality is essential to avoid overgeneralization or inappropriate extrapolation.

1.3. Scale mismatches limit relevance for human impacts

A further challenge arises from the spatial and temporal scales at which most vegetation–climate models operate. Regional and global climate models typically represent vegetation changes as shifts in fractional plant functional type coverage within grid cells and report area–averaged responses. These scales are disconnected from microclimatic processes governing human exposure, including shading, radiation, humidity, wind, and built form (Havenith and Fiala, 2015; Lin et al., 2025; McDonald et al., 2026). In contrast to efforts to increase surface albedo, lower–albedo leaves can enhance transpiration-based cooling (Rahman et al., 2020). Accordingly, regional changes in summer near–surface air temperature, disproportionately reflecting rural or sparsely inhabited areas, should not be interpreted as proportional changes in heat risk, which is collectively determined by hazard, exposure, and vulnerability (Chakraborty et al., 2023). Moreover, temperature–mortality relationships are typically U–shaped, with elevated risks at cold and hot extremes and sensitivity to prior exposure (Pintor, 2024), such that ignoring seasonal asymmetries may mislead decision makers about population heat–health risks (Wang et al., 2025).

1.4. Future scenario dependence constrains generalizability

Many vegetation–climate modelling studies draw conclusions about vegetation–driven climate effects based on a single emissions or socioeconomic scenario, despite substantial uncertainty in future forcing pathways. Land–atmosphere interactions, vegetation drought responses, and background radiative forcing differ substantially across scenarios, particularly among mitigation–oriented pathways and high–emission futures (O'Neill et al., 2016; Zhang et al., 2025). The magnitude, and in some cases even the sign of vegetation responses and accompanying biophysical and ecological change, may therefore depend on the broader climate state in which those changes are embedded. Evaluating the "climate effectiveness" under only one or two scenarios should be strictly interpreted as conditional on that climate trajectory and associated warming, aridity, and circulation changes. Multi–scenario analysis has been widely recommended in land–climate studies to characterize uncertainty and nonlinear interactions between vegetation processes and background climate forcing (Schleussner et al., 2024; Snover et al., 2013). Without such context, conclusions drawn from single–scenario simulations should always be framed as contingent rather than generalizable. Interpreting modelled reductions in air temperature as evidence of broader climate effectiveness or ecosystem service enhancement may extend beyond the intended scope of the modelling framework and contribute to maladaptive policy decisions.

1.5. Interpreting forest-to-grassland conversion requires particular caution

As indicated above, some vegetation–climate modelling studies report summer near–surface air–temperature reductions associated with forest loss or forest–to–grassland conversion under specific modelled conditions (Yao et al., 2025). While such results are mechanistically consistent with albedo–driven cooling in certain climates and time frames (Lee et al., 2011; Williams et al., 2021), they should not be interpreted as policy–relevant recommendations without broader ecological, biogeochemical, and human–contextual considerations. This is critical to avoid overgeneralized and erroneous conclusions.

Specifically, while high–albedo grasslands might reduce daytime summer air temperatures under certain model assumptions, such cooling may coincide with reduced carbon storage, altered hydrological regimes, diminished biodiversity, increased drought vulnerability, and degraded ecosystem services (Bright et al., 2015; Luyssaert et al., 2018). These trade–offs are particularly important in contexts where winter warming, fuel loads, and species transition dynamics complicate simple temperature–based assessments. Moreover, empirical studies do not consistently show that grasses cool the near–surface atmosphere more effectively than forests across all conditions (Guo et al., 2026). In the case of ecosystem services related to human thermal exposure, observational work has shown that trees can produce greater cooling at typical human heights (e.g., ~1.5 m) than grasses, with grass cooling exceeding tree cooling only very close to the surface under specific conditions (Crum and Jenerette, 2017). Accordingly, focusing narrowly on air temperature change following vegetation conversion may provide an incomplete basis for assessing broader ecosystem-service outcomes or climate effectiveness.

2. Conclusions

Vegetation–climate models are essential tools for understanding land–atmosphere processes, isolating biophysical mechanisms, and quantifying individual ecosystem services. However, the simplifications inherent in these models define the boundaries of their applicability and the ecosystem services they can meaningfully assess. Interpreting temperature responses as comprehensive indicators of climate regulation effectiveness, ecosystem service supply, or human heat stress risks overlooking structural assumptions, physiological constraints, scale mismatches, and scenario dependencies that condition model outputs. Responsible use of these models requires clear communication of scope and conditionality, particularly when results are framed and translated into policy narratives. Assessing temperature responses alongside carbon storage, hydrological feedbacks, ecosystem services, and real–world human exposure provides a more complete basis for informing mitigation and adaptation strategies. A key challenge is how to weigh different dimensions of climate relevance across spatial and temporal scales, including tradeoffs among biogeophysical cooling, carbon storage, biodiversity, and ecosystem resilience. Addressing these tradeoffs will require greater integration across modelling and observational approaches and explicit consideration of ecosystem services.

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Theodore A. Endreny: Writing – review & editing, Writing – original draft, Project administration, Methodology, Conceptualization. **TC Chakraborty:** Writing – review & editing, Writing – original draft, Visualization, Methodology. **Javier Diez-Sierra:** Writing – review & editing. **Manuel Esperon-Rodriguez:** Writing – review & editing, Writing – original draft, Methodology. **Rüdiger Grote:** Writing – review & editing, Writing – original draft, Methodology. **Christopher Claus Holst:** Writing – review & editing, Writing – original draft, Methodology. **Rob McDonald:** Writing – review & editing, Writing – original draft, Methodology. **Philipp Porada:** Writing – review & editing, Methodology. **Nadine Ruehr:** Writing – review & editing. **Chenghao Wang:** Writing – review & editing, Writing – original draft, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data were used for the research described in the article.

References

Alkama, R., Cescatti, A., 2016. Biophysical climate impacts of recent changes in global forest cover. Science 351 (6273), 600–604.

Amali, A.A., Schwingshackl, C., Ito, A., Barbu, A., Delire, C., Peano, D., et al., 2025. Biogeochemical versus biogeophysical temperature effects of historical land-use change in CMIP6. Earth Syst. Dyn. 16 (3), 803–840. https://esd.copernicus.org/articles/16/803/2025/.

Arora, V.K., Montenegro, A., 2011. Small temperature benefits provided by realistic afforestation efforts. Nat. Geosci. 4 (8), 514–518. https://doi.org/10.1038/ngeo1182.

Bright, R.M., Zhao, K., Jackson, R.B., Cherubini, F., 2015. Quantifying surface albedo and other direct biogeophysical climate forcings of forestry activities. Glob. Chang. Biol. 21 (9), 3246–3266. https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.12951.

Chakraborty, T.C., Newman, A.J., Qian, Y., Hsu, A., Sheriff, G., 2023. Residential segregation and outdoor urban moist heat stress disparities in the United States. One Earth 6 (6), 738–750. https://www.sciencedirect.com/science/article/pii/S2590332223002506.

Choat, B., Brodribb, T.J., Brodersen, C.R., Duursma, R.A., López, R., Medlyn, B.E., 2018. Triggers of tree mortality under drought. Nature 558 (7711), 531–539.

Crum, S.M., Jenerette, G.D., 2017. Microclimate variation among urban land covers: the importance of vertical and horizontal structure in air and land surface temperature relationships. J. Appl. Meteorol. Climatol. 56 (9), 2531–2543. https://journals.ametsoc.org/view/journals/apme/56/9/jamc-d-17-0054.1.xml.

Devaraju, N., de Noblet-Ducoudré, N., Quesada, B., Bala, G., 2018. Quantifying the relative importance of direct and indirect biophysical effects of deforestation on surface temperature and teleconnections. J. Climate 31 (10), 3811–3829. https://journals.ametsoc.org/view/journals/clim/31/10/jcli-d-17-0563.1.xml.

Ehbrecht, M., Seidel, D., Annighöfer, P., Kreft, H., Köhler, M., Zemp, D.C., et al., 2021. Global patterns and climatic controls of forest structural complexity. Nat. Commun. 12 (1), 519. https://doi.org/10.1038/s41467-020-20767-z.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., et al., 2005. Global consequences of land use. Science 309 (5734), 570–574. Review. <Go to ISI>://000230735200036.

Guo, Z., Esperon-Rodriguez, M., Davin, E., Huang, H., Chen, B., Hejazi, M., et al., 2026. Global urban vegetation exhibits divergent thermal effects: from cooling to warming as aridity increases. Sci. Adv. 12 (1), eaea9165. https://www.science.org/doi/abs/10.1126/sciadv.aea9165.

Havenith, G., Fiala, D., 2015. Thermal indices and thermophysiological modeling for heat stress. Compr. Physiol. 6 (1), 255–302.

Lee, K., Hong, J.W., Kim, J., Jo, S., Hong, J., 2021. Traces of urban forest in temperature and CO2 signals in monsoon East Asia. Atmos. Chem. Phys. 21 (23), 17833–17853. https://acp.copernicus.org/articles/21/17833/2021/.

Lee, X., Goulden, M.L., Hollinger, D.Y., Barr, A., Black, T.A., Bohrer, G., et al., 2011. Observed increase in local cooling effect of deforestation at higher latitudes. Nature 479 (7373), 384–387. https://doi.org/10.1038/nature10588.

Li, K., Kuppel, S., Knighton, J., 2023. Parameterizing vegetation traits with a process-based ecohydrological model and xylem water isotopic observations. J. Adv. Model. Earth Syst. 15 (1), e2022MS003263. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2022MS003263.

Lin, G.-S., Llaguno-Munitxa, M., Manoli, G., 2025. Daily and seasonal human mobility modulates temperature exposure in European cities. PloS One 20 (9), e0330912. https://doi.org/10.1371/journal.pone.0330912.

Luyssaert, S., Marie, G., Valade, A., Chen, Y.-Y., Njakou Djomo, S., Ryder, J., et al., 2018. Trade-offs in using European forests to meet climate objectives. Nature 562 (7726), 259–262. https://doi.org/10.1038/s41586-018-0577-1.

McDonald, R.I., Chakraborty, T.C., Endreny, T.A., Parsons, L.A., Marsagishvili, M., Esperon-Rodriguez, M., 2026. Trees halve urban heat island effect globally but unequal benefits only modestly mitigate climate-change warming. Nat. Commun. 17 (1), 3569. https://doi.org/10.1038/s41467-026-71825-x.

O'Neill, B.C., Tebaldi, C., van Vuuren, D.P., Eyring, V., Friedlingstein, P., Hurtt, G., et al., 2016. The scenario model intercomparison project (ScenarioMIP) for CMIP6. Geosci. Model Dev. 9 (9), 3461–3482. https://gmd.copernicus.org/articles/9/3461/2016/.

Pintor, M.P., 2024. The future of the temperature-mortality relationship. Lancet Public Health 9 (9), e636–e637. https://doi.org/10.1016/S2468-2667(24)00184-1.

Rahman, M.A., Stratopoulos, L.M.F., Moser-Reischl, A., Zolch, T., Haberle, K.H., Rotzer, T., et al., 2020. Traits of trees for cooling urban heat islands: a meta-analysis. Build. Environ. *170*. <Go to ISI>://WOS:000519374700002.

Schleussner, C.-F., Ganti, G., Lejeune, Q., Zhu, B., Pfleiderer, P., Prütz, R., et al., 2024. Overconfidence in climate overshoot. Nature 634 (8033), 366–373. https://doi.org/10.1038/s41586-024-08020-9.

Smith, A.C., Harrison, P.A., Pérez Soba, M., Archaux, F., Blicharska, M., Egoh, B.N., et al., 2017. How natural capital delivers ecosystem services: a typology derived from a systematic review. Ecosyst. Serv. 26, 111–126. https://www.sciencedirect.com/science/article/pii/S2212041617300086.

Snover, A.K., Mantua, N.J., Littell, J.S., Alexander, M.A., Mcclure, M.M., Nye, J., 2013. Choosing and using climate-change scenarios for ecological-impact assessments and conservation decisions. Conserv. Biol. 27 (6), 1147–1157. https://conbio.onlinelibrary.wiley.com/doi/abs/10.1111/cobi.12163.

Wang, S., Zhan, W., Zhou, B., Tong, S., Chakraborty, T.C., Wang, Z., et al., 2025. Dual impact of global urban overheating on mortality. Nat. Clim. Chang. 15 (5), 497–504. https://doi.org/10.1038/s41558-025-02303-3.

Williams, C.A., Gu, H., Jiao, T., 2021. Climate impacts of U.S. forest loss span net warming to net cooling. Sci. Adv. 7 (7), eaax8859. https://doi.org/10.1126/sciadv.aax8859.

Wright, J.S., Fu, R., Worden, J.R., Chakraborty, S., Clinton, N.E., Risi, C., et al., 2017. Rainforest-initiated wet season onset over the southern Amazon. Proc. Natl. Acad. Sci. 114 (32), 8481–8486. https://www.pnas.org/doi/abs/10.1073/pnas.1621516114.

Yao, Y., Sieber, P., Hauser, M., Schwaab, J., Jäger, F., Batibeniz, F., et al., 2025. Conversion from coniferous to broadleaved trees can make European forests more climate-effective. Nat. Commun. 16 (1), 9536. https://doi.org/10.1038/s41467-025-64580-y.

Zhang, Y., Lv, J., Wang, T., Zhang, K., Wu, Y., 2025. Assessment of ecological risk under different SSP-RCP scenarios of the Xinjiang province in China. Sci. Rep. 15 (1), 8345. https://doi.org/10.1038/s41598-024-81879-w.