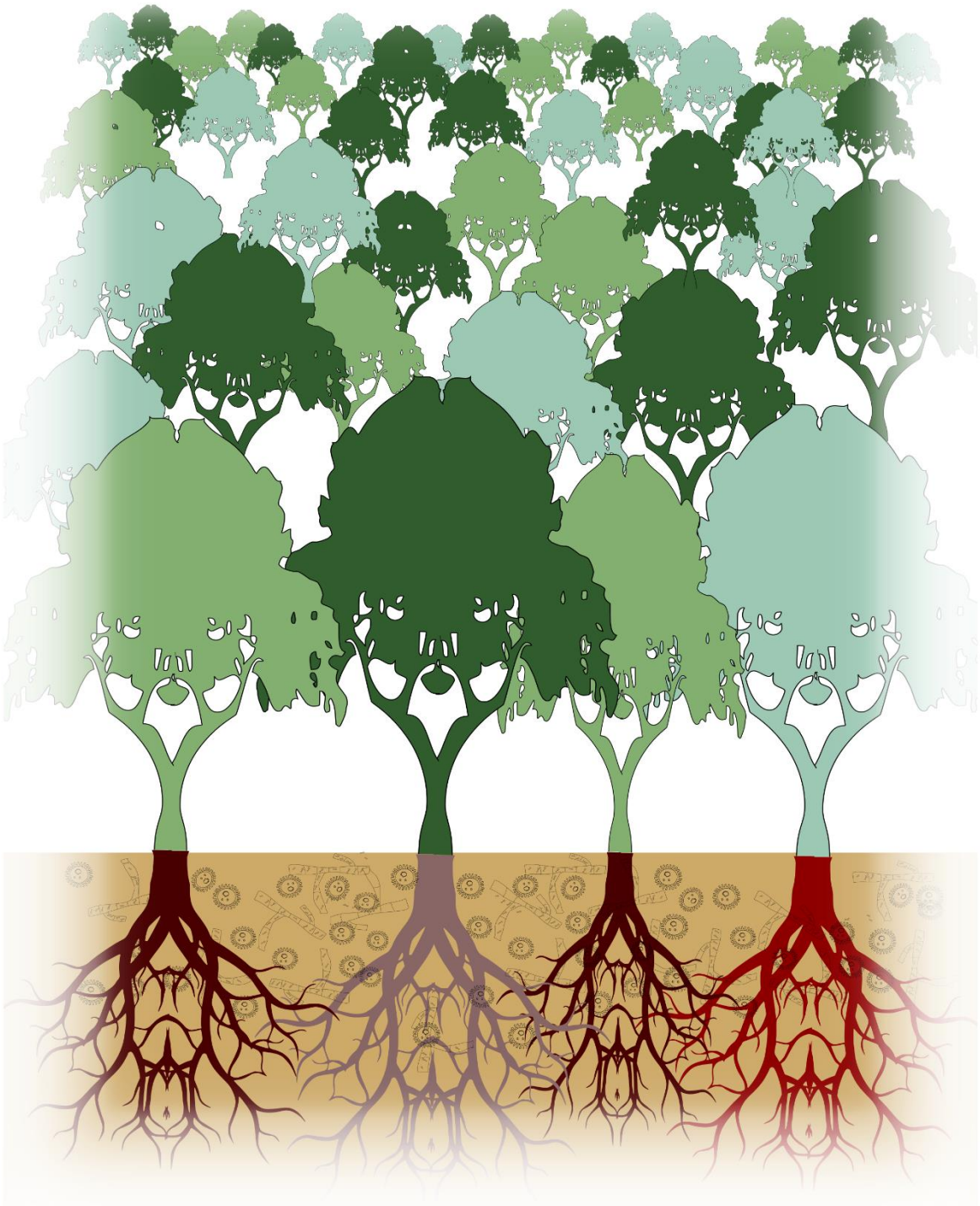

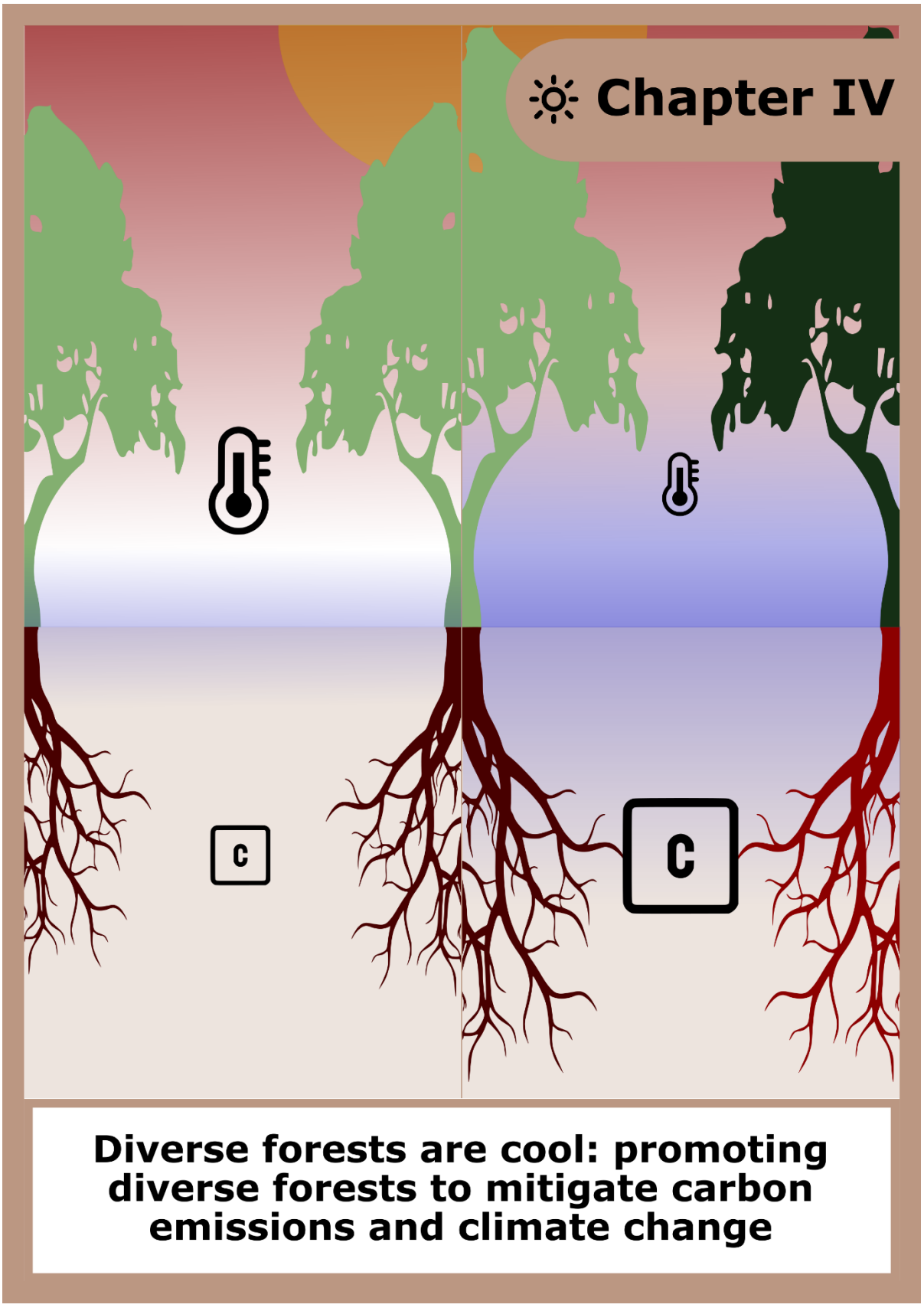

Diverse forests are cool: promoting diverse forests to mitigate carbon emissions and climate change

Chapter IV – Diverse forests are cool: promoting diverse forests to mitigate carbon emissions and climate change

Rémy Beugnon[c, 1, 2], Emma Ladouceur[1, 2, 3], Marie Sünnemann[1, 2], Simone Cesarz[1, 2, S] & Nico Eisenhauer[1, 2, S]

[s]: senior authors, [c]: corresponding author, email: remy.beugnon@idiv.de

[1]: German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Puschstrasse 4, 04103 Leipzig, Germany

[2]: Institute of Biology, Leipzig University, Puschstrasse 4, 04103 Leipzig, Germany

[3]: Department of Physiological Diversity, Helmholtz Centre for Environmental Research - UFZ, Permoserstrasse 15, 04318 Leipzig, Germany

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Abstract

Climate change is one of the most pressing threats to humanity, inducing a global increase in temperatures and more frequent extreme climatic events. Considering this, global reforestation initiatives are proposed to capture carbon and mitigate climate change. Global restoration and reforestation programs and their targets have inspired both unparalleled enthusiasm worldwide and intense scientific criticism and debate regarding their feasibility and implementation. We agree that global reforestation forecasting and efforts require a nuanced discussion and approach. In that vein, we would like to emphasize the potential of increasing existing forest diversity to enhance climate change mitigation by increasing aboveground and belowground carbon storage. Moreover, we argue that focusing on planting diverse forests in reforestation efforts can help to reduce climate change effects on ecosystems: first, by increasing resistance and resilience to extreme climatic events, and second, by buffering microclimatic conditions in natural and urban areas. Diversifying forests plantations and reforestation projects may not always be feasible and cannot solve the climate crisis by itself. However, we highlight that a focus on diverse forests could maximize the benefits of reforestation programs by promoting sustainable land management.

Climate change and nature-based mitigation

Climate change threatens humanity and other life on Earth (IPCC 2013, 2021). The IPCC reports (2013, 2021) highlighted the crucial role of anthropogenic carbon dioxide (CO_2) emissions in climate change, estimating that CO_2 emissions contributed to about 0.75°C of the 1°C global warming over the last century (IPCC 2013, 2021). In addition to global warming, climate change induces more frequent and intense extreme climatic events, such as heatwaves and droughts. Enhancing photosynthetic carbon capture by increasing tree cover and restoring degraded forests has been suggested as one of the most effective approaches to mitigate climate change (Bastin *et al.* 2019; Lewis *et al.* 2019b). The IPCC (2013) projected that 1 billion ha of forest would be needed to keep global warming increases below 1.5°C by 2050 (IPCC 2013). This estimate was downscaled by Bastin *et al.* (2019), who predicted that planting 0.9 billion ha could store 205 Gt of carbon while investigating available areas for reforestation worldwide (Bastin *et al.* 2019). However, these numbers have been heavily criticized since their

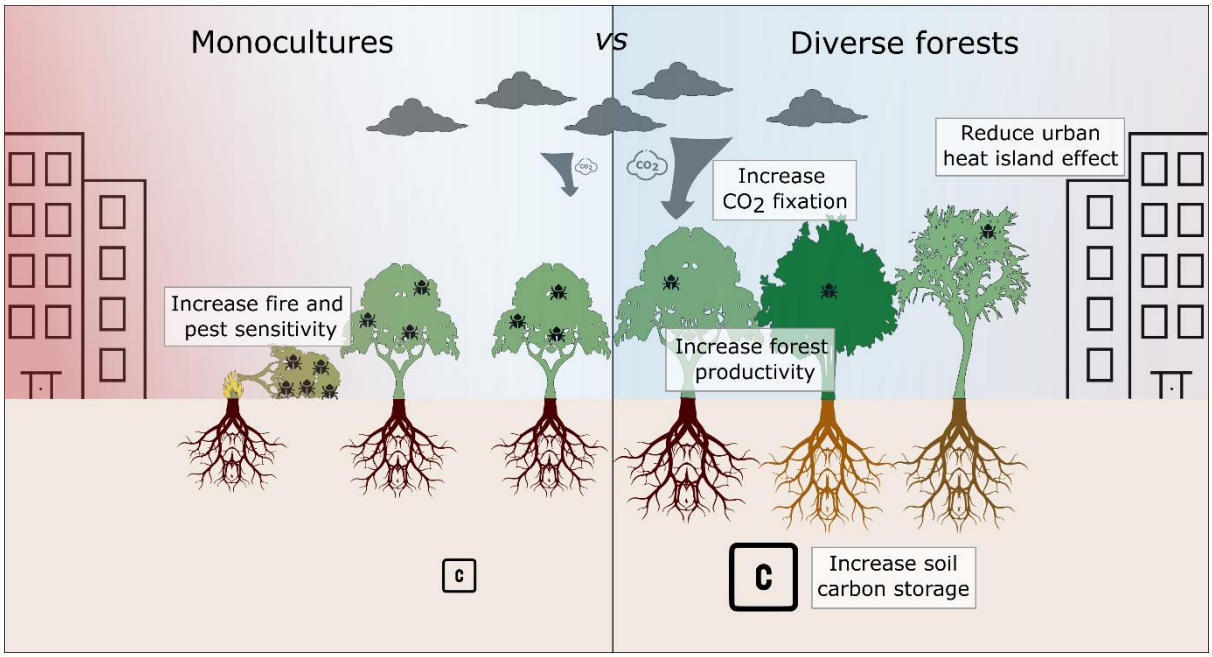

Figure IV.1: Conceptual figure of the effects of tree diversity on ecosystem properties related to climate change mitigation. Briefly, diverse forests have been shown to fix more carbon from the atmosphere, store more carbon above- and belowground, decrease the likelihood and severity of fires and pest outbreaks, and mitigate microclimatic conditions under climate change.

publication (Skidmore *et al.* 2019; Lewis *et al.* 2019a). The main concern is that the study overestimated the carbon storage potential of forests, thus underestimating the land area needed to achieve current carbon storage goals. Therefore, one major source of debate is that a global reforestation initiative to store 205 Gt of carbon would compete with other land uses (e.g., cropland, urban areas).

Diversifying forests to mitigate carbon emissions

There is increasing evidence that tree diversity has a positive effect on multiple measures of ecosystem functioning in forests (i.e., multifunctionality; Schuldt *et al.* 2018; Messier *et al.* 2021; Gamfeldt *et al.* 2013). Especially diverse forests were shown to increase aboveground (Huang *et al.* 2018; Duffy *et al.* 2017) and belowground (Xu *et al.* 2020; Liu *et al.* 2018) carbon storage (Fig. IV.1), e.g. by increasing tree complementarity while reducing soil carbon loss by erosion (Schuldt *et al.* 2018; Huang *et al.* 2018; Williams *et al.* 2017). For instance, in subtropical climates, species-rich forests of 20 tree species per ha store three times more carbon than monocultures (Liu *et al.* 2018). We argue that diversifying existing forests and reforestation projects will increase and stabilize forest carbon storage, therefore reducing the land needed for global reforestation projects, and thus the competition for land between reforestation projects and other important land uses. However, even if these patterns seem to be consistent globally (Xu *et al.* 2020), better global coverage of research across biomes is needed to predict the carbon storage potential of locally diversified forests. Promising initiatives in this context include the increasing availability of forest inventory data (e.g., Craven *et al.* 2020), the global network of tree diversity experiments (TreeDivNet; Verheyen *et al.* 2016), and global restoration initiatives with a biodiversity focus (e.g., Restor[1]). Likewise, promoting species-rich plantations will enhance the carbon storage potential of managed

[1] https://restor.eco/

forests in addition to reforestation projects. Transdisciplinary projects are needed to understand both biodiversity and production constraints and objectives (Messier *et al.* 2021). Here, we suggest that biodiversity-ecosystem functioning (BEF) research should take a sharp turn toward transdisciplinary research to better meet the practical demands of land managers, practitioners, and restoration initiatives (Messier *et al.* 2021). For instance, Mao *et al.* (2021) proposed and applied a holistic modeling framework to link biodiversity conservation and socio-economic goals in French mountain resort areas (Mao *et al.* 2021).

Diverse forests to mitigate the consequences of climate change

Climate change is expected to increase the frequency and intensity of extreme climatic events as well as biological responses to those events, such as drought, fire, and insect outbreaks (Messier *et al.* 2021; Pureswaran *et al.* 2018), increasing tree mortality and reducing forest heath. Climate change could contribute to reduce forest cover in the tropics by more than 200 million ha by 2050 (Bastin *et al.* 2019). Concurrently, tree diversity experiments have shown the high potential of diverse forests to buffer extreme climatic events (see Grossiord 2020 for context-dependencies; Fichtner *et al.* 2020). For example, tree diversity mitigates drought effects on forest productivity (Fichtner *et al.* 2020) by increasing the asynchronous response of tree species to climatic variability (Schnabel *et al.* 2019), thereby stabilizing ecosystem services (Messier *et al.* 2021; Gamfeldt *et al.* 2013). Likewise, increasing tree diversity stabilizes long-term carbon storage by reducing forests' susceptibility to fire and thus the net release of carbon dioxide (Messier *et al.* 2021). Moreover, diverse forests are naturally resistant to extreme insect outbreaks and herbivory pressure by supporting multitrophic biodiversity (Schuldt *et al.* 2018; Jactel *et al.* 2021). Given the many advantages that diverse forests provide, promoting diverse forests in existing forests and in reforestation projects present multiple benefits to protect forests from climate change in a sustainable way (Fig. IV.1).

Diverse forests to increase human well-being in cities

In cities - where most humans live - temperature increase is amplified by sealed surfaces and a lack of vegetation (so-called urban heat island effect), intensifying summer heatwaves, and exacerbating intense climatic effects on human well-being (IPCC 2021). Increasing urban tree cover and planting urban forests have been shown to reduce the urban heat island effect and to improve human well-being by shading surfaces (Gamfeldt *et al.* 2013). Urban forests could account for up to 1% of the total global reforestation potential (Bastin *et al.* 2019), which is an efficient space to improve millions of lives. Simultaneously, tree diversity increases aboveground productivity in forests (Huang *et al.* 2018; Duffy *et al.* 2017) and tree crown structural complementarity (Williams *et al.* 2017). Therefore, we expect tree diversity to increase canopy buffering of macroclimatic fluctuations (Frenne *et al.* 2021) and thus reduce the microclimatic temperature below the canopy under warm conditions (Gottschall *et al.* 2019). Increasing tree diversity in and around the urban matrix has the potential to enhance forest cooling effects (Fig. IV.1), but more experimental work is needed to explore this phenomenon and its magnitude. Here, we argue that public policy should take advantage of urban areas to plant diverse forests locally and contribute to climate change mitigation while increasing population well-being.

Outlook

We argue that diversifying existing forests and planting diverse forests through reforestation programs will promote forest carbon storage and can thus contribute to climate change mitigation. Moreover, increasing tree diversity will promote forest multifunctionality and protect forest functioning against climate change-induced threats (e.g., extreme climatic events, insect outbreaks). Finally, we suggest that tree diversity should be promoted in urban areas to locally buffer warming while improving human well-being. There is strong momentum for re-

/afforestation initiatives like the UN Decade on Ecosystem Restoration (2021-2030)[2], the Bonn Challenge[3], and the European Green Deal[4], as well as sustainable management of forests (see UN Sustainable Development Goals[5]: 6, 11, 13, 15). We acknowledge that reforestation is not possible everywhere and may also impose serious pitfalls, like the reduction of water availability or increase of social iniquity (Holl and Brancalion 2020). Therefore, to increase the likelihood of success of these initiatives, transdisciplinary approaches are needed to connect scientists, land managers, and politicians to address sustainable land use and climate change mitigation. Further research is essential to better assess how diverse forests will maximize reforestation potential to mitigate climate change. In particular, we need to determine the conditions under which diversifying forests is feasible (Holl and Brancalion 2020) and which tree community will provide the greatest benefits, and the limits under which diverse forests can mitigate the effects of climate change and extreme climatic events.

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[2] https://wedocs.unep.org/bitstream/handle/20.500.11822/30919/UNDecade.pdf?sequence=7
[3] https://www.bonnchallenge.org/content/challenge
[4] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
[5] https://sdgs.un.org/

References

Bastin, Jean-Francois; Finegold, Yelena; Garcia, Claude; Mollicone, Danilo; Rezende, Marcelo; Routh, Devin et al. (2019): The global tree restoration potential. In *Science (New York, N.Y.)* 365 (6448), pp. 76–79. DOI: 10.1126/science.aax0848.

Craven, Dylan; Sande, Masha T.; Meyer, Carsten; Gerstner, Katharina; Bennett, Joanne M.; Giling, Darren P. et al. (2020): A cross-scale assessment of productivity–diversity relationships. In *Global Ecology and Biogeography* 29 (11), pp. 1940–1955. DOI: 10.1111/geb.13165.

Duffy, J. Emmett; Godwin, Casey M.; Cardinale, Bradley J. (2017): Biodiversity effects in the wild are common and as strong as key drivers of productivity. In *Nature* 549 (7671), pp. 261–264. DOI: 10.1038/nature23886.

Fichtner, Andreas; Schnabel, Florian; Bruelheide, Helge; Kunz, Matthias; Mausolf, Katharina; Schuldt, Andreas et al. (2020): Neighbourhood diversity mitigates drought impacts on tree growth. In *Journal of Ecology* 108 (3), pp. 865–875. DOI: 10.1111/1365-2745.13353.

Frenne, Pieter de; Lenoir, Jonathan; Luoto, Miska; Scheffers, Brett R.; Zellweger, Florian; Aalto, Juha et al. (2021): Forest microclimates and climate change: Importance, drivers and future research agenda. In *Global Change Biology* 27 (11), pp. 2279–2297. DOI: 10.1111/gcb.15569.

Gamfeldt, Lars; Snäll, Tord; Bagchi, Robert; Jonsson, Micael; Gustafsson, Lena; Kjellander, Petter et al. (2013): Higher levels of multiple ecosystem services are found in forests with more tree species. In *Nature communications* 4 (1), p. 1340. DOI: 10.1038/ncomms2328.

Gottschall, Felix; Davids, Sophie; Newiger-Dous, Till E.; Auge, Harald; Cesarz, Simone; Eisenhauer, Nico (2019): Tree species identity determines wood decomposition via microclimatic effects. In *Ecology and Evolution* 9 (21), pp. 12113–12127. DOI: 10.1002/ece3.5665.

Grossiord, Charlotte (2020): Having the right neighbors: how tree species diversity modulates drought impacts on forests. In *The New phytologist* 228 (1), pp. 42–49. DOI: 10.1111/nph.15667.

Holl, Karen D.; Brancalion, Pedro H. S. (2020): Tree planting is not a simple solution. In *Science (New York, N.Y.)* 368 (6491), pp. 580–581. DOI: 10.1126/science.aba8232.

Huang, Yuanyuan; Chen, Yuxin; Castro-Izaguirre, Nadia; Baruffol, Martin; Brezzi, Matteo; Lang, Anne et al. (2018): Impacts of species richness on productivity in a large-scale subtropical forest experiment. In *Science (New York, N.Y.)* 362 (6410), pp. 80–83. DOI: 10.1126/science.aat6405.

IPCC (Ed.) (2013): IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. With assistance of T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung et al. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPCC (Ed.) (2021): IPCC 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. With assistance of V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger et al. IPCC. Cambridge: Cambridge University Press.

Jactel, Hervé; Moreira, Xoaquín; Castagneyrol, Bastien (2021): Tree Diversity and Forest Resistance to Insect Pests: Patterns, Mechanisms, and Prospects. In *Annual Review of Entomology* 66 (1), pp. 277–296. DOI: 10.1146/annurev-ento-041720-075234.

Lewis, Simon L.; Mitchard, Edward T. A.; Prentice, Colin; Maslin, Mark; Poulter, Ben (2019a): Comment on "The global tree restoration potential". In *Science (New York, N.Y.)* 366 (6463), eaaz0388. DOI: 10.1126/science.aaz0388.

Lewis, Simon L.; Wheeler, Charlotte E.; Mitchard, Edward T. A.; Koch, Alexander (2019b): Restoring natural forests is the best way to remove atmospheric carbon. In *Nature* 568 (7750), pp. 25–28. DOI: 10.1038/d41586-019-01026-8.

Liu, Xiaojuan; Trogisch, Stefan; He, Jin-Sheng; Niklaus, Pascal A.; Bruelheide, Helge; Tang, Zhiyao et al. (2018): Tree species richness increases ecosystem carbon storage in subtropical forests. In *Proceedings. Biological sciences* 285 (1885). DOI: 10.1098/rspb.2018.1240.

Mao, Zhun; Centanni, Julia; Pommereau, Franck; Stokes, Alexia; Gaucherel, Cédric (2021): Maintaining biodiversity promotes the multifunctionality of social-ecological systems: holistic modelling of a mountain system. In *Ecosystem Services* 47, p. 101220. DOI: 10.1016/j.ecoser.2020.101220.

Messier, Christian; Bauhus, Jürgen; Sousa-Silva, Rita; Auge, Harald; Baeten, Lander; Barsoum, Nadia et al. (2021): For the sake of resilience and multifunctionality, let's diversify planted forests! In *Conservation Letters*. DOI: 10.1111/conl.12829.

Pureswaran, Deepa S.; Roques, Alain; Battisti, Andrea (2018): Forest Insects and Climate Change. In *Current Forestry Reports* 4 (2), pp. 35–50. DOI: 10.1007/s40725-018-0075-6.

Schnabel, Florian; Schwarz, Julia A.; Dănescu, Adrian; Fichtner, Andreas; Nock, Charles A.; Bauhus, Jürgen; Potvin, Catherine (2019): Drivers of productivity and its temporal stability in a tropical tree diversity experiment. In *Global Change Biology* 25 (12), pp. 4257–4272. DOI: 10.1111/gcb.14792.

Schuldt, Andreas; Assmann, Thorsten; Brezzi, Matteo; Buscot, François; Eichenberg, David; Gutknecht, Jessica et al. (2018): Biodiversity across trophic levels drives multifunctionality in highly diverse forests. In *Nature communications* 9 (1), p. 2989. DOI: 10.1038/s41467-018-05421-z.

Skidmore, Andrew K.; Wang, Tiejun; Bie, Kees de; Pilesjö, Petter (2019): Comment on "The global tree restoration potential". In *Science (New York, N.Y.)* 366 (6469), eaaz0111. DOI: 10.1126/science.aaz0111.

Verheyen, Kris; Vanhellemont, Margot; Auge, Harald; Baeten, Lander; Baraloto, Christopher; Barsoum, Nadia et al. (2016): Contributions of a global network of tree diversity experiments to sustainable forest plantations. In *Ambio* 45 (1), pp. 29–41. DOI: 10.1007/s13280-015-0685-1.

Williams, Laura J.; Paquette, Alain; Cavender-Bares, Jeannine; Messier, Christian; Reich, Peter B. (2017): Spatial complementarity in tree crowns explains overyielding in species mixtures. In *Nature ecology & evolution* 1 (4), p. 63. DOI: 10.1038/s41559-016-0063.

Xu, Shan; Eisenhauer, Nico; Ferlian, Olga; Zhang, Jinlong; Zhou, Guoyi; Lu, Xiankai et al. (2020): Species richness promotes ecosystem carbon storage: evidence from biodiversity-ecosystem functioning experiments. In *Proceedings. Biological sciences* 287 (1939), p. 20202063. DOI: 10.1098/rspb.2020.2063.