The Critical Importance of Mature & Old Trees for Climate Resilience

Available scientific evidence strongly suggests that logging mature trees and forests will often undermine climate resilience on federal forests. For a variety of reasons, mature and old trees tend to be well positioned to survive the disturbance-enhancing effects of climate change. These trees develop structural and physiological attributes with age that enable them to better resist disturbance-induced mortality (e.g., thicker bark, higher crowns, deeper roots, etc.).[1] Evidence to suggest that mature trees are more vulnerable to increased mortality from climate change compared to younger trees remains limited.[2] While forests are becoming increasingly vulnerable to various stressors, some theories about increasing forest resilience to climate change through logging remain largely speculative—particularly when applied to entire landscapes.[3] Moreover, logging mature trees and forests is well-known to significantly reduce or even eliminate many of the key natural values they provide.[4] The relative resistance of mature trees and stands to climate change, as well as the well-established negative effects of logging them, point toward the critical importance of protecting mature and old trees from logging on federal lands.

Research indicates that mature and old trees are often better equipped to survive natural disturbances, including those being exacerbated by climate change, than their younger counterparts. Big trees tend to have adaptive traits that allow them to survive fire, including thick bark, open crowns, comparatively high moisture content,[5] and tall canopies that favorably modify the local microclimate and near-surface fuel conditions.[6] There is also no consensus from empirical studies that bigger, older trees are necessarily more vulnerable to drought[7]—and research suggests that such trees often have physiological mechanisms (e.g., larger root volume and depth) to help them better withstand drought.[8] Additionally, mature and old-growth forests and trees can increase resilience to insect outbreaks because the complex structure of mature and old forests often supports a greater abundance and diversity of insectivores (even while some insects target the bigger trees of certain species).[9] Contrary to the popular assertion that trees weaken as they grow old, recent research indicates that vulnerability to disturbances—particularly drought and/or insects—tends to be more a function of species than age.[10] Striking examples of forest dieback do exist and are projected to continue or increase with climate change.[11] But there is limited evidence that either mature forests or mature trees experience increased mortality as compared to younger cohorts.[12] Striking examples of forest dieback do exist and are

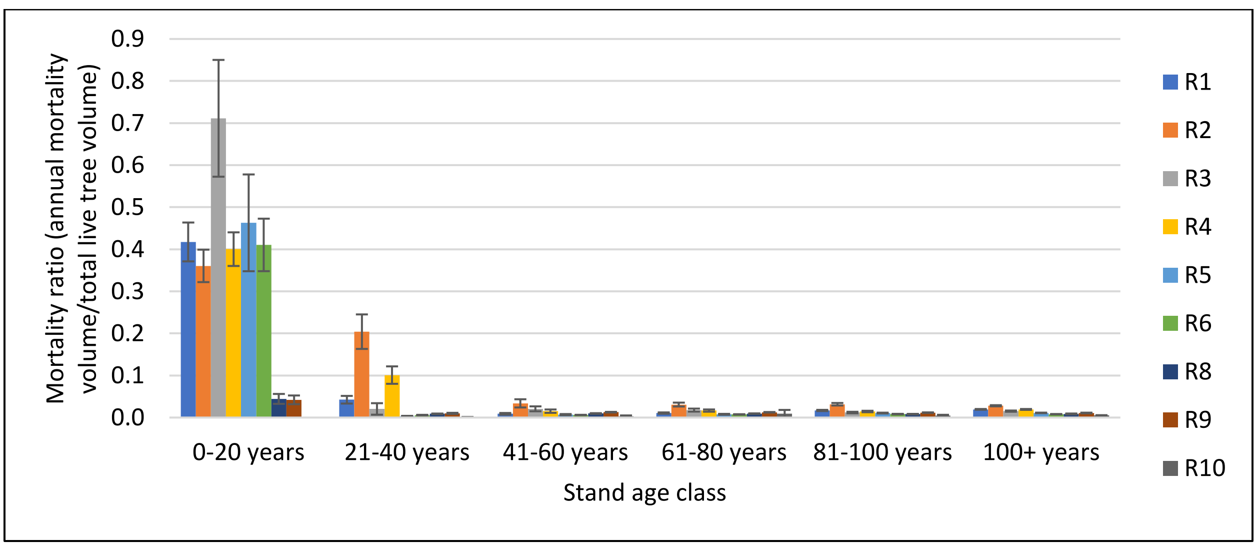


Figure 1. Annual mortality ratio (the annual mortality sound bole volume of trees ≥ 5 in. DBH in cubic feet on forest land/total live sound bole volume of trees ≥ 5 in. DBH in cubic feet on forest land) vs. stand age class. Data queried from FIA using EVALIDator. Legend shows USFS regions.

projected to continue or increase with climate change.[13] But there is limited evidence that either mature forests or mature trees experience increased mortality as compared to younger cohorts.[14]

Beyond the existing mortality literature, figure 1 above corroborates that there is no generalizable trend of increasing mortality with stand age. This analysis used annual mortality ratio data extracted from FIA using EVALIDator to demonstrate proportional mortality rather than total mortality without context for stand size and age distribution on USFS forests. The data indicate that proportionally significantly more trees in young stands (0-40 years) are dying. The data beyond 40 years indicate that there is no increasing trend in mortality with stand age. These mortality ratio data are further broken down in the appendix by four different primary disturbances related to climate change: insect, disease, fire, and drought damage. Similarly, while these breakdowns by disturbance certainly show sometimes significant mortality in older age classes, they do not show generalizable trends of increasing mortality with stand age.

Research also suggests that older trees and forests are often relatively more resistant to heat and drought stress, potentially because of higher moisture retention capabilities, larger mycorrhizae networks, and/or more effective water transport systems.[15] Consistent with this, other research has shown that the resilience of unmanaged stands to disturbance is typically greater than it is for managed ones.[16] And where mature forests and trees do experience mortality from disturbance events, their dead and fallen biomass continue to provide a range of important natural values, including carbon storage and critical wildlife habitat.[17] The presence of older trees and stands thus generally enhances the overall climate resilience of a given landscape, while also provisioning for other natural values like biodiversity and watershed integrity.[18]

It is also important to acknowledge that the efficacy of active management regimes to confer resilience relative to the effects of climate change is often speculative. While broad climate trends have been established (e.g., the western U.S. becoming increasingly hot and dry), there is limited consensus on the specific nature of site-specific conditions that will occur under future warming scenarios.[19] For example, while evapotranspiration is expected to increase and water yields to decrease on many national forests under some climate scenarios, the reverse is true under others.[20] Also, notwithstanding substantial research activity, fundamental questions about the efficacy of some fuels treatments—such as thinning—remain to be answered.[21] And the evidence that thinning can mitigate the effect of drought on growth response and recovery often focuses on species-specific responses among young trees and/or in younger stands, with little

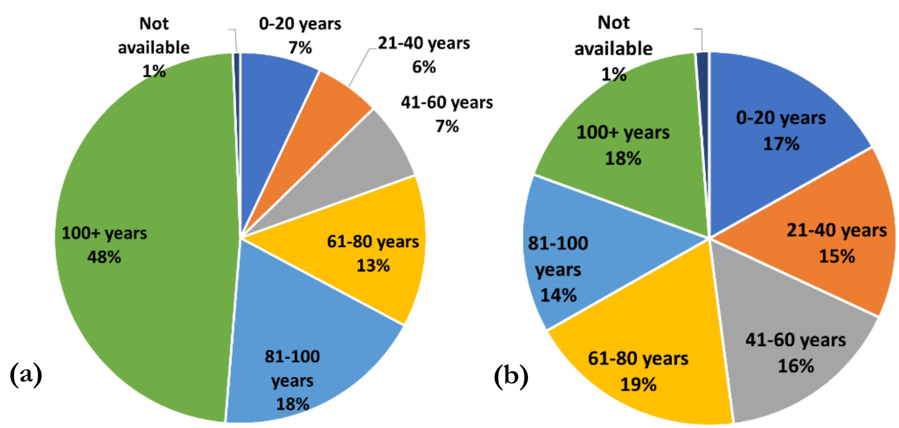


Figure 2. (a) Total carbon on USFS forested lands by stand age class; (b) USFS forest area vs. stand age class (data queried from FIA using EVALIDator tool)

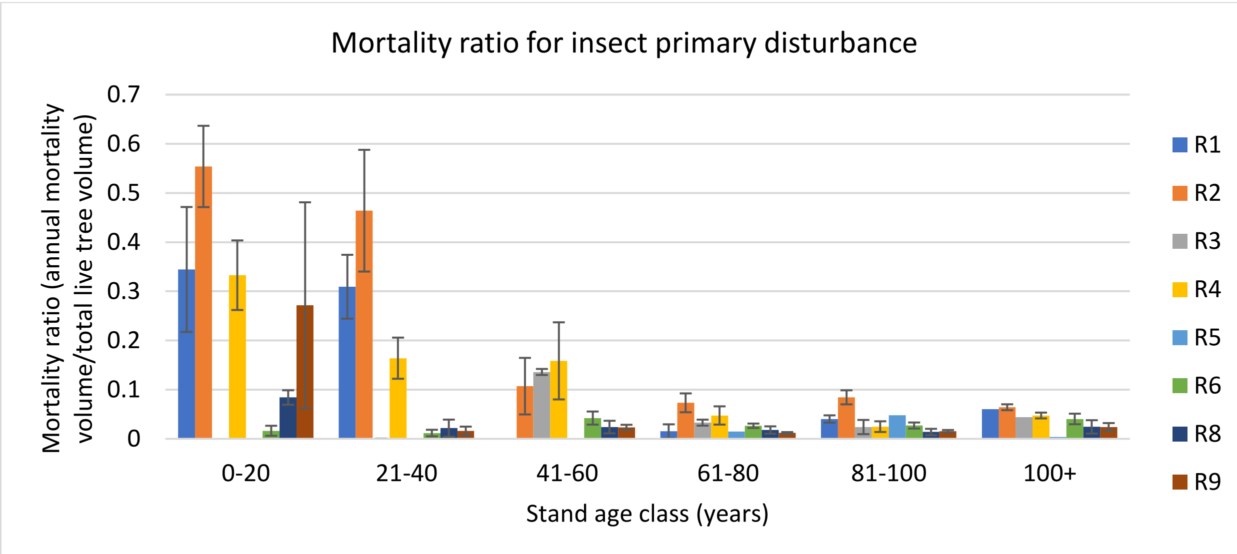
research on the efficacy of removing mature trees or the cascading effects of such mature tree removals on overall ecosystem health.[22] More broadly, what might be seen as stagnated growth and recovery following a drought could actually be acclimation that will protect that tree or stand from future disturbance more effectively than more direct human interventions.[23] Additionally, logging to increase resistance to insect-related mortality has shown mixed results (and, indeed, can undermine forest resilience along other axes).[24] While thinning stands early in a bark beetle outbreak can sometimes mitigate tree mortality, thinning does not stop a bark beetle outbreak once it has become an epidemic, and typically causes more harm than benefit.[25] Up until now there has been limited research on the success of active management intended to increase climate adaptation and resilience, and most predictions of benefit rely heavily on models, which have a number of significant limitations.[26]

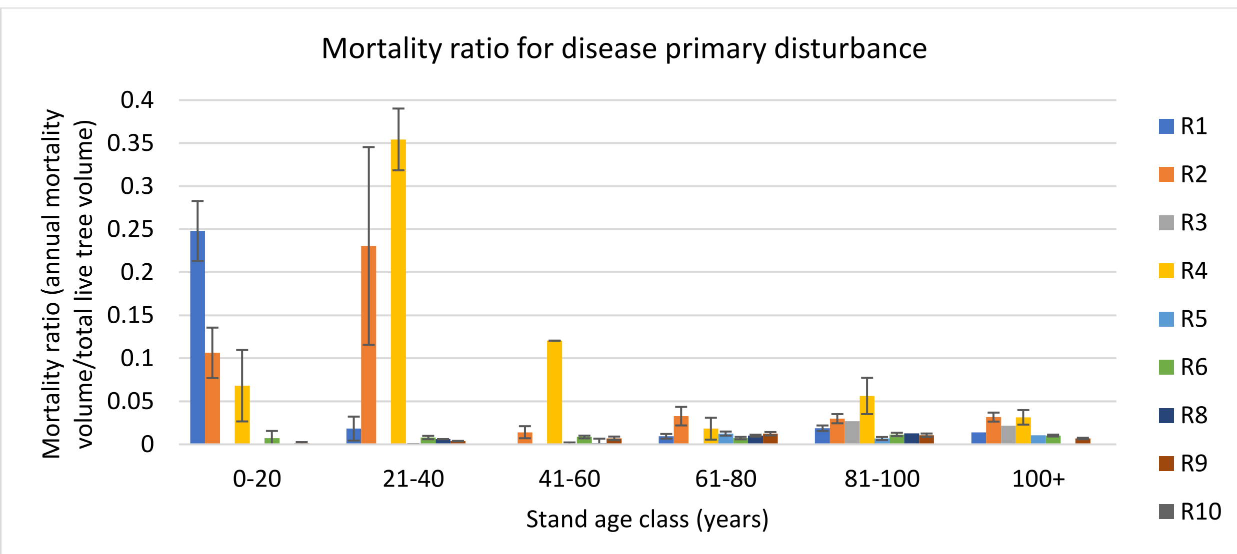
In contrast, the scientific evidence documenting the numerous important and irreplaceable values associated with mature forests and trees is well-established. The proportion of carbon stored ($2/3^{rds}$) in mature and old-growth forests and trees (i.e., those at least 80 years old) far exceeds the proportion of acres ($1/3^{rd}$) that they occupy, across forest types, as shown in Figure 2 from FIA data. This finding stands without even including the significant carbon stores in large trees outside of mature and old-growth stands. Older trees hold significantly more carbon than younger trees, and their annual rate of carbon sequestration generally increases as they age.[27] After a forest stand enters maturity, it often continues to accumulate carbon at a significantly high rate for extended periods of time.[28] Large, dead trees can continue to store carbon for centuries, as they slowly decompose when left as snags or coarse woody debris (CWD) on the forest floor.[29] Mature stands develop complex habitats as they age that support significant—and often imperiled—biodiversity.[30] They also regulate hydrological cycles, often preventing water from quickly evaporating or running off the landscape.[31] Due to their increasing rarity and unique attributes, mature and old forest habitats are becoming even more important under changing climatic conditions. Relatively cool, moist areas can serve as climate refugia for species that are sensitive to temperature increases in a warming world.[32]

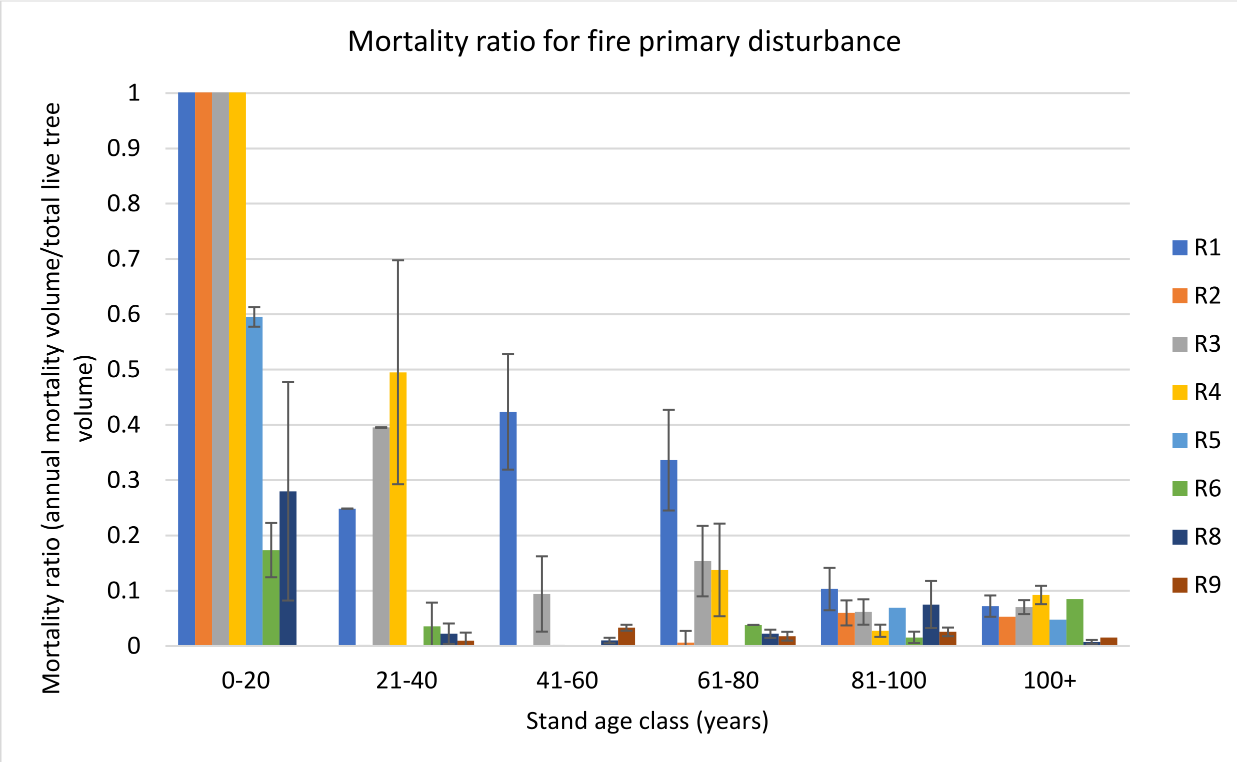
Based on the foregoing discussion, we argue strongly for a cautious, carefully considered use of active management techniques when applied to mature or old-growth trees in dry, disturbance-adapted forests, and we note there is no ecological justification for active management of older trees and stands in more mesic/wetter forest types as this could actually constitute maladaptive management.[33] This view is in part a reflection of the potential for active management of such forests and trees to produce unforeseen negative outcomes, as well as the need to preserve treatment options until we have better empirical evidence—rather than committing vast swaths of federal lands to unproven management theories with unknown long-range effects.[34] The kind of conservative, measured approach advocated here is also based upon well-established facts about the numerous irreplaceable values of mature and old-growth forests and trees and their increasing rarity relative to historical conditions.

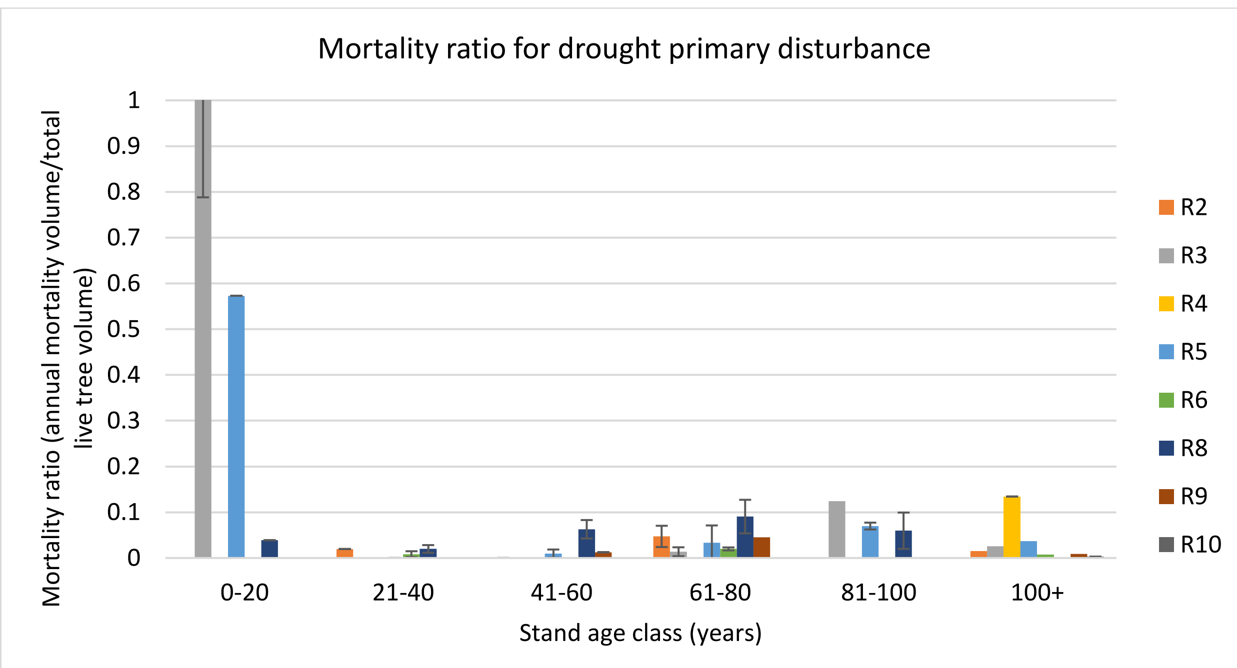
Appendix: Mortality ratios for USFS regions categorized by primary disturbance

All data for the primary disturbance mortality ratio plots were queried from FIA using EVALIDator. All error bars for plots are from the standard error output from EVALIDator. While the increased mortality ratios for the 0-20 year stand age class may partially be due to background mortality of saplings/seedlings, we note of importance that there are no consistent trends showing that older stands are dying at higher rates. There do appear to be data gaps in the mortality ratio data, notably for disease and drought, but from what data are available, these data show that there is not a need to log mature and old-growth stands because of increased mortality.






Mortality ratio for fire primary disturbance
Mortality ratio (annual mortality volume/total live tree volume)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0-20
21-40
41-60
61-80
81-100
100+
Stand age class (years)
R1
R2
R3
R4
R5
R6
R8
R9


Mortality ratio for drought primary disturbance
Mortality ratio (annual mortality volume/total live tree volume)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0-20
21-40
41-60
61-80
81-100
100+
Stand age class (years)
R2
R3
R4
R5
R6
R8
R9
R10

[1] Agee, J. Fire Ecology of Pacific Northwest Forests. Washington, D.C.: Island Press. 1993, 121-24; Brown, P.M., et al. "Identifying old trees to inform ecological restoration in montane forests of the central Rocky Mountains, USA." *Tree Ring Research* (2019) 75 (1): 34-48. https://doi.org/10.3959/1536-1098-75.1.34.

[2] Van Mantgem, P.J. et al. "Widespread increase of tree mortality rates in the western United States." *Science* (2009) 323: 521-524. https://doi.org/10.1126/science.1165000; McNellis, B. E. et al. "Tree mortality in western U.S. forests forecasted using forest inventory and Random Forest classification." *Ecosphere* (2021) 12(3):e03419. https://doi.org/10.1002/ecs2.3419.

[3] Agra, H. et al. "Forest conservation." In: "What works in conservation" *Open Book Publishers* (2020) 323-366. Edited by W.J. Sutherland et al. https://www.openbookpublishers.com/books/10.11647/obp.0191; Fettig, C. J. et al. "The Effectiveness of Vegetation Management Practices for Prevention and Control of Bark Beetle Infestations in Coniferous Forests of the Western and Southern United States." *For. Ecol. Manag.* (2007) 238 (1), 24–53. https://doi.org/10.1016/j.foreco.2006.10.011; Six, D. L. et al. "Management for Mountain Pine Beetle Outbreak Suppression: Does Relevant Science Support Current Policy?" *Forests* (2014) 5 (1), 103–133. https://doi.org/10.3390/f5010103.

[4] Donato, D.C. et al. "Evaluating post-outbreak management effects on future fuel profiles and stand structure in bark beetle-impacted forests of Greater Yellowstone." *Forest Ecology and Management* (2013) 303: 160–174. https://doi.org/10.1016/j.foreco.2013.04.022; Patton, R.M. et al. "Management trade-offs between forest carbon stocks, sequestration rates and structural complexity in the central Adirondacks." *Forest Ecology and Management* (2022) 525: 120539. https://doi.org/10.1016/j.foreco.2022.120539; Young, B.D. et al. "Seven decades of change in forest structure and composition in *Pinus resinosa* forests in northern Minnesota, USA: Comparing managed and unmanaged conditions." *Forest Ecology and Management* (2017) 395: 92–103. https://doi.org/10.1016/j.foreco.2017.04.003.

[5] Agee, J.K. "Fire Ecology of Pacific Northwest Forests." *Island Press* (1993) 121–124; Brown, P.M. et al. "Identifying old trees to inform ecological restoration in montane forests of the central Rocky Mountains, USA." *Tree Ring Research* (2019) 75(1): 34–48. https://doi.org/10.3959/1536-1098-75.1.34.

[6] Stevens, J.T. "Fire resistance trait data for 29 western North American conifer species." *U.S. Geological Survey data release* (2020). https://doi.org/10.5066/P97F5P7L; Habeck, R.J. "Fire Effects Information System (FEIS): Sequoiadendron giganteum." *U.S. Forest Service* (1992).

[7] Fernandez-de-Una, L. et al. "The role of height-driven constrains and compensation on tree vulnerability to drought." *New Phytologist* (2023). https://doi.org/10.1111/nph.19130; Camarero, J. J. "The drought-dieback-death conundrum in trees and forests." *Plant Ecology and Diversity* (2021) 14: 1-12. https://doi.org/10.1080/17550874.2021.1961172; Trugman, A.T. "Why is tree drought mortality so hard to predict?" *Trends in Ecology and Evolution* (2021) 36: P520-532. https://doi.org/10.1016/j.tree.2021.02.001; Camarero, J. "Within- versus between-species size effects on drought-induced dieback and mortality." *Tree Physiology* (2020) 41: 679-682. https://doi.org/10.1093/treephys/tpaa167; Clark, J.S. et al. "The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States." *Global Change Biology* (2016) 22: 2329-2352. https://doi.org/10.1111/gcb.13160.

[8] Xu, B. et al. "Seasonal variability of forest sensitivity to heat and drought stresses: A synthesis based on carbon fluxes from North American forest ecosystems." *Global Change Biology* (2020) 26(2), 901-918. http://dx.doi.org/10.1111/gcb.14843; Pardos, M. et al. "The greater resilience of mixed forests to drought mainly depends on their composition: Analysis along a climate gradient across Europe." *Forest Ecology and Management* (2021) 481, 118687. https://doi.org/10.1016/j.foreco.2020.118687.

[9] Schowalter T. "Arthropod Diversity and Functional Importance in Old-Growth Forests of North America." *Forests* (2017) 8(4):97. https://doi.org/10.3390/f8040097.

[10] McNellis, B. E. et al. "Tree mortality in western U.S. forests forecasted using forest inventory and Random Forest classification." *Ecosphere* (2021) 12(3):e03419. https://doi.org/10.1002/ecs2.3419; Anderegg, W. et al. "Consequences of widespread tree mortality triggered by drought and temperature stress." *Nature Climate Change* (2013) 3, 30–36. https://doi.org/10.1038/nclimate1635.

[11] Van Mantgem, P.J. et al. "Widespread increase of tree mortality rates in the western United States." *Science* (2009) 323: 521-524. https://doi.org/10.1126/science.1165000.

[12] *Ibid.*

[13] Van Mantgem, P.J. et al. "Widespread increase of tree mortality rates in the western United States." *Science* (2009) 323: 521-524. https://doi.org/10.1126/science.1165000.

[14] *Ibid.*

[15] Agee, J.K. "Fire Ecology of Pacific Northwest Forests." *Island Press* (1993) 121–124; Brown, P.M. et al. "Identifying old trees to inform ecological restoration in montane forests of the central Rocky Mountains, USA." *Tree Ring Research* (2019) 75(1): 34–48. https://doi.org/10.3959/1536-1098-75.1.34; McNellis, B. E. et al. "Tree mortality in western U.S.

forests forecasted using forest inventory and Random Forest classification." *Ecosphere* (2021) 12(3):e03419. https://doi.org/10.1002/ecs2.3419; Gilhen-Baker, M. et al. "Old growth forests and large old trees as critical organisms connecting ecosystems and human health. A review." Environmental Chemistry Letters (2022) 20: 1529–1538. https://doi.org/10.1007/s10311-021-01372-y; Augé, R.M. et al. "Moisture retention properties of a mycorrhizal soil." Plant and Soil (2001) 230: 87–97. https://doi.org/10.1023/A:1004891210871; Rillig, M.C. and D.L. Mummey. "Mycorrhizas and soil structure." New Phytologist (2006) 171(1): 41– 53. https://doi.org/10.1111/j.1469-8137.2006.01750.x.

[16] Miller, K.M. et al. "National parks in the eastern United States harbor important older forest structure compared with matrix forests." *Ecosphere* (2016) 7: e01404. https://doi.org/10.1002/ecs2.1404; Miller, K.M. et al. "Eastern national parks protect greater tree species diversity than unprotected matrix forests." *Forest Ecology and Management* (2018) 414: 74–84. https://doi.org/10.1016/j.foreco.2018.02.018; Forzieri, G. et al. "Emerging signals of declining forest resilience under climate change." *Nature* (2022) 608: 534–539. https://doi.org/10.1038/s41586-022-04959-9; Faison, E.K. et al. "Adaptation and mitigation capacity of wildland forests in the northeastern United States." Forest Ecology and Management (2023) 544: 121145. https://doi.org/10.1016/j.foreco.2023.121145.

[17] He, L. et al. "Relationships between net primary productivity and forest stand age in U.S. forests." Global Biogeochemical Cycles (2012) 26(3). https://doi.org/10.1029/2010GB003942; Law, B.E. et al. "Changes in carbon storage and fluxes in a chronosequence of ponderosa pine." Global Change Biology (2003) 9(4): 510–524. https://doi.org/10.1046/j.1365-2486.2003.00624.x; Keeton, W.S. et al. "Late-Successional Biomass Development in Northern Hardwood-Conifer Forests of the Northeastern United States." Forest Science (2011) 57(6): 489–505. https://academic.oup.com/forestscience/article/57/6/489/4604514; Harmon, M.E. et al. "Ecology of coarse woody debris in temperate ecosystems." Advances in Ecological Research (2004) 34: 59-234. https://doi.org/10.1016/S0065-2504(03)34002-4; Lutz, J.A. et al. "The importance of large-diameter trees to the creation of snag and deadwood biomass." Ecological Processes (2021) 10: 28. https://doi.org/10.1186/s13717-021-00299-0.

[18] Pypker, T.G. et al. "The role of epiphytes in rainfall interception by forests in the Pacific Northwest. I. Laboratory measurements of water storage." Canadian Journal of Forest Research (2006) 36(4). https://doi.org/10.1139/x05-298; Crampe, E.A. et al. "Fifty years of runoff response to conversion of old-growth forest to planted forest in the H. J. Andrews Forest, Oregon, USA." Hydrological Processes (2021) 35(5): e14168. https://doi.org/10.1002/hyp.14168; Franklin, J.F. et al. "Ecological Forest Management," Waveland Press (2018); Perry, D.A. "Forest Ecosystems." Johns Hopkins University Press (1994).

[19] Shafer, S.L. et al. "Potential changes in the distributions of western North America tree and shrub taxa under future climate scenarios." *Ecosystems* (2001) 4: 200–215. https://doi.org/10.1007/s10021-001-0004-5; Norlen, C.A. & Goulden, M.L. "Recent Tree Mortality Dampens Semi-Arid Forest Die-Off During Subsequent Drought." AGU Advances (2023) 4: e2022AV000810. https://doi.org/10.1029/2022AV000810.

[20] Heidari, H. et al. "Impacts of climate change on hydroclimatic conditions of U.S. national forests and grasslands." *Forests* (2012) 12(2): 139. https://doi.org/10.3390/f12020139.

[21] Omi, P. "Theory and practice of wildland fuels management." *Current Forestry Reports* (2015) 1: 100-117. https://doi.org/10.1007/s40725-015-0013-9; Raymond, C. and D.L. Peterson. "How did prefire treatments affect the Biscuit Fire?" *Fire Management Today* (2005) 65(2): 18-22. https://www.fs.usda.gov/research/treesearch/24900; Campbell, J.L. et al. "Can fuel-reduction treatments really increase forest carbon storage in the western US by reducing future fire emissions?" *Frontiers in Ecology and the Environment* (2011) 10(2):83-90. https://doi.org/10.1890/110057; Moreau, G. et al. "Opportunities and limitations of thinning to increase resistance and resilience of trees and forests to global change." *Forestry*: *An International Journal of Forest Research* (2022) 95, 5, 595–615. https://doi.org/10.1093/forestry/cpac010.

`[22] Sohn, J. A. et al. "Potential of forest thinning to mitigate drought stress: A meta-analysis." *Forest Ecology and Management* (2016) 380, 261-273. https://doi.org/10.1016/j.foreco.2016.07.046; Law, B. E. et al. "Thinning effects on forest productivity: consequences of preserving old forests and mitigating impacts of fire and drought." *Plant Ecology & Diversity* (2013) 6:1, 73-85, https://doi.org/10.1080/17550874.2012.679013.

[23] Gessler, A. et al. "The way back: recovery of trees from drought and its implication for acclimation." *New Phytologist* (2020) 228: 1704-1709. https://doi.org/10.1111/nph.16703.

[24] Fettig, C. J. et al. "The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the Western and Southern United States." *Forest Ecology and Management* (2007) 238(1): 24–53. https://doi.org/10.1016/j.foreco.2006.10.011; Nowak, J. T. et al. "Southern Pine Beetle infestations in relation to forest stand conditions, previous thinning, and prescribed burning: Evaluation of the Southern Pine Beetle Prevention Program." *Journal of Forestry* (2015) 113(5): 454–462. https://doi.org/10.5849/jof.15-002; Black, S.H. et al. "Do bark beetle outbreaks increase wildfire risks in the central U.S. Rocky Mountains? Implications from recent

research." *Natural Areas Journal* (2013) 33(1): 59–65. https://doi.org/10.3375/043.033.0107; Six, D.L. et al. "Management for mountain pine beetle outbreak suppression: Does relevant science support current policy?" *Forests* (2014) 5: 103–133. https://doi.org/10.3390/f5010103; Black, S.H. et al. "Insects and roadless forests: A scientific review of causes, consequences and management alternatives." *National Center for Conservation Science and Policy* (2010). https://xerces.org/sites/default/files/2018-05/10-004_02_XercesSoc_Insects%2BRoadless-Forests_web.pdf; Black, S. H. et al. "Insects and roadless forests: A scientific review of causes, consequences and management alternatives." *National Center for Conservation Science and Policy* (2010); DellaSala, D. A. et al. "A critical role for core reserves in managing inland Northwest landscapes for natural resources and biodiversity." *Wildlife Society Bulletin 1973-2006* (1996), 24(2): 209–221. https://www.jstor.org/stable/3783109.

[25] Black, S. H. et al. "Do Bark Beetle Outbreaks Increase Wildfire Risks in the Central U.S. Rocky Mountains? Implications from Recent Research." *Natural Areas Journal* (2013) 33 (1), 59–65. https://doi.org/10.3375/043.033.0107; Fettig, C. J. et al. "The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the Western and Southern United States." *Forest Ecology and Management* (2007) 238(1): 24–53. https://doi.org/10.1016/j.foreco.2006.10.011;

[26] Prober, S.M. et al. "Shifting the conservation paradigm: a synthesis of options for renovating nature under climate change." *Ecological Monographs* (2019) 89(1): e01333. https://doi.org/10.1002/ecm.1333; Parmesan, C. et al. "Terrestrial and freshwater ecosystems and their services." In: "Climate change 2022: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change." *Cambridge University Press* (2022) 197-377. Edited by H. Pörtner et al. https://doi.org/10.1017/9781009325844.004; Agra, H. et al. "Forest conservation." In: "What works in conservation" *Open Book Publishers* (2020) 323-366. Edited by W.J. Sutherland et al. https://www.openbookpublishers.com/books/10.11647/obp.0191.

[27] Stephenson, N.L. et al. "Rate of tree carbon accumulation increases continuously with tree size." Nature (2014) 507: 90–93. https://doi.org/10.1038/nature12914.

[28] He, L. et al. "Relationships between net primary productivity and forest stand age in U.S. forests." Global Biogeochemical Cycles (2012) 26(3). https://doi.org/10.1029/2010GB003942; Birdsey, R.A. et al. "Assessment of the influence of disturbance, management activities, and environmental factors on carbon stocks of U.S. national forests." USDA Forest Service Gen. Tech. Rep. RMRS-GTR-402. Rocky Mountain Research Station, Fort Collins, CO (2019). https://www.fs.usda.gov/sites/default/files/Appendix-4-NFS-Disturbance-Carbon-Assessment-Southern-Region.pdf; Birdsey R.A. et al. "Assessing carbon stocks and accumulation potential of mature forests and larger trees in U.S. federal lands." Frontiers in Forests and Global Change (2023) 5: 1074508. https://doi.org/10.3389/ffgc.2022.1074508.

[29] Lutz, J.A. et al. "The importance of large-diameter trees to the creation of snag and deadwood biomass." Ecological Processes (2021) 10: 28. https://doi.org/10.1186/s13717-021-00299-0; Kelsey, R.G. et al. "Changes in heartwood chemistry of dead yellow-cedar trees that remain standing for 80 years or more in Southeast Alaska." Journal of Chemical Ecology (2005) 31: 2653–2670. https://doi.org/10.1007/s10886-005-7618-6; Harmon, M.E. et al. "Ecology of coarse woody debris in temperate ecosystems." Advances in Ecological Research (2004) 34: 59-234. https://doi.org/10.1016/S0065-2504(03)34002-4.

[30] Brandt, P. et al. "Multifunctionality and biodiversity: Ecosystem services in temperate rainforests of the Pacific Northwest, USA." Biological Conservation (2014) 169: 362–371. https://doi.org/10.1016/j.biocon.2013.12.003; Franklin, J.F. et al. "Ecological Forest Management." Waveland Press (2018); Perry, D.A. "Forest Ecosystems." Johns Hopkins University Press (1994).

[31] Crampe, E.A. et al. "Fifty years of runoff response to conversion of old-growth forest to planted forest in the H. J. Andrews Forest, Oregon, USA." Hydrological Processes (2021) 35(5): e1s4168. https://doi.org/10.1002/hyp.14168; Nagy, R.C. et al. "Water resources and land use and cover in a humid region: the Southeastern United States." Journal of Environmental Quality. (2011) 40(3): 867-878. https://doi.org/10.2134/jeq2010.0365; Aron, P.G. et al. "Stable water isotopes reveal effects of intermediate disturbance and canopy structure on forest water cycling." Journal of Geophysical Research (2019) 124(10): 2958-2975. https://doi.org/10.1029/2019JG005118; Perry, T.D. and J.A. Jones. "Summer streamflow deficits from regenerating Douglas-fir forest in the Pacific Northwest, USA." Ecohydrology (2017) 10(2): 1790. https://doi.org/10.1002/eco.1790.

[32] Frey S.J. et al. "Spatial models reveal the microclimatic buffering capacity of old-growth forests." Science Advances (2016) 2(4): e1501392. https://doi.org/10.1126/sciadv.1501392.

[33] Faison, E.K. et al. "Adaptation and mitigation capacity of wildland forests in the Northeastern United States." Forest Ecology and Management (2023) 554: 121145. https://doi.org/10.1016/j.foreco.2023.121145; Birdsey R.A. et al. "Assessment of the influence of disturbance, management activities, and environmental factors on carbon stocks of U.S. national forests." USDA Forest Service Gen. Tech. Rep. RMRS-GTR-402. Rocky Mountain Research Station, Fort Collins, CO (2019). https://doi.org/10.2737/RMRS-GTR-402; Moomaw W.R. et al. "Intact Forests in the United

States: Proforestation Mitigates Climate Change and Serves the Greatest Good." Frontiers in Forests and Global Change (2019) 2: 27. https://doi.org/10.3389/ffgc.2019.00027; Lorimer, C.G. and A.S. White. "Scale and frequency of natural disturbances in the northeastern US: implications for early successional forest habitats and regional age distributions." Forest Ecology and Management (2003) 185(1–2): 41-64. https://doi.org/10.1016/S0378-1127(03)00245-7; Fisichelli, N.A., et al. "Is 'Resilience' Maladaptive? Towards an Accurate Lexicon for Climate Change Adaptation." *Environmental Management* (2016) 57, 753–758. https://doi.org/10.1007/s00267-015-0650-6.

[34] Schoennagel, T. and C.R. Nelson. "Restoration relevance of recent National Fire Plan treatments in forests of the western United States." Frontiers in Ecology and the Environment (2010) 9(5): 271-277 https://doi.org/10.1890/090199; Six, D.L. et al. "Management for Mountain Pine Beetle outbreak suppression: Does relevant science support current policy?" Forests (2014) 5(1): 103-133. https://doi.org/10.3390/f5010103.