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The DEIS Amendments To LMPs To Address Old Growth Forests is one of the most self-serving documents generated by the Forest Service in recent memory. Rather than complying with the underlying "intent" of Executive Order 14072, the DEIS follows the "letter" of the EO and is but another example of the Forest Service management's history of "form over substance."

For example, the DEIS (p. 74) admits that "Vegetation management can be a stressor in old-growth forests," but then qualifies that confession by asserting that "but it can also be an important driver of restoration and positive transformation (USDA and USDI 2024b)" - referencing no independent research, only internally produced documents.

The DEIS (p. 74) claims "Silvicultural approaches can aid in restoring old-growth attributes by mimicking natural forest dynamics and promoting structural complexity and biodiversity (Ducey et al. 2013, Bauhaus et al. 2009)." If this assertion is indeed valid, the agency should have been able to find more recent research that validates the declaration. As more recent research refutes the assertion, the agency has conveniently ignored its existence.

The DEIS (p. 74) goes on to claim that "Thinning can accelerate individual tree growth, aiding in the restoration of large trees and old forest structures (Case et al. 2023)." Although thinning may accelerate individual tree growth, old-growth forest structures are complex and consist of uncountable and interconnected ecosystems. Again, the Forest Service discounts the fact that an increasing amount of research shows that thinning and most other on-the-ground management activities damage or destroy many of the ecosystems that comprise old-growth forests. With its focus only on trees, the agency cherry-picks research, much of it produced by USDA employees, to support the contention that it MUST perform on-the-ground management actions to protect old-growth forests.

The DEIS (p. 75) states "Many management activities like removing hazardous fuels and reducing live tree density or activities enhancing species, structural, or age-class diversity may have short-term carbon emissions but yield long-term carbon benefits through enhancing forest resiliency and therefore carbon stabilization (Krofcheck et al. 2019, Puhlick et al. 2020; Crockett et al. 2023)." Careful research into forest harvesting, including thinning, reveals that logging causes the majority of forest carbon emissions, many times that of natural disturbances. Forest management asserts that regrowth will eventually sequester the carbon that was removed. That speculation is based on assumed future conditions and ignores the fact that any carbon currently released into the atmosphere will remain in the atmosphere for many hundreds of years, continuously contributing to additional global warming.

The DEIS (p. 75) further states that "Carbon may also be transferred to harvested wood products (HWP) or used for energy production, while increasing longer-term forest productivity and health (Sathre and O'Connor 2010, D'Amato et al. 2011, Oliver et al. 2014)." There are many claims that the use of wood harvested from forests should be substituted for other building materials (steel and concrete) higher carbon footprints. Articles written about this subject, including the above-referenced studies, usually fall short by omitting portions of the life cycle of wood products and overestimate the willingness of the building industry to adjust to different materials.

The DEIS (p. 75) claims that "The Intergovernmental Panel on Climate Change (IPCC) recognizes wood as a renewable resource that when sustainably managed can mitigate climate change (IPCC, 2022b). Assessing impacts of harvest on GHGs thus should include carbon storage estimates from wood products." The assumption that because the IPCC recognized wood [products] as a renewable resource is particularly ludicrous. Although a sizable worldwide team of scientists participate in the production of IPCC reports, the final documents are not made public until after they are edited and approved by politicians. The IPCC recognition of wood products as renewable resources was and remains a political, not scientific, decision.

Mitigating global warming requires a drastic reduction in fossil fuel use and an increase in the sequestration and storage of carbon. The Forest Service is not only ignoring fossil fuel use but is increasing and will continue to increase its use by implementing the DEIS as currently written. Additionally, the on-the-ground management activities approved by the DEIS reduce forest above- and below-ground carbon storage and substantially decrease forests' sequestration ability.

Attached is a 2024 meta-analysis of forest carbon sequestration and storage which supports the allegation that the on-the-ground management activities contained in this DEIS are not based upon scientific research but on political expediency.

Respectfully submitted,

/S/ M L Hoyt

Improving Carbon Sequestration and StorageA Meta-Analysis of 65 Years of Published LiteratureBy Michael HoytAugust 12, 2024Executive SummaryThis paper looks at how changing the focus of forest management would significantly improve the sequestering and long-term storage of carbon.The analysis of substantially more than 200 research articles published since 1960 revealed that current forest-management activities, both public and private, do not take full advantage of the sequestration and storage capacity of forested areas. In most cases forested areas are managed for extractive purposes (i.e., the production of timber).Over the last several decades scientific research has shown forest ecosystems provide wildlife habitat, help maintain biodiversity, deliver and store clean water, sequester and store carbon, and that forests should not simply be managed as tree farms. The emphasis for forest management by the United States Forest Service (USFS) has changed little and remains focused on the production of timber. What has transformed is the agency's justification for why its emphasis remains on extraction.The agency no longer admits managing forests as if trees are a crop, but asserts its focus is on improving forest health and protecting them from disturbance (e.g., wildfire, insects, and disease). Interestingly, in its attempts to accomplish those goals, the USFS uses the same methods used since the formation of the agency (i.e., logging and thinning). Because on-the-ground methods and the ways they are implemented have not altered, a reasonable question is whether agency explanations used for current management actions are sincere.Climate scientists have established that Earth is experiencing global warming because of the continuing increase of greenhouse gases in the atmosphere. To moderate the consequences of the rapidly warming climate, fossil fuel emissions must be drastically reduced or eliminated and greenhouse gases, especially atmospheric carbon dioxide (CO2) and methane (CH4), must be reduced as quickly as possible. Here, the topic is the removal of atmospheric CO2 using forests to sequester and store carbon (C).Technological schemes, most of which require the consumption of substantial amounts of energy, are being suggested as solutions to transferring atmospheric CO2 to long-term storage. However, relying on the natural carbon cycles of forests is immediate, far less expensive, and does not require the consumption of human-produced energy.The most recent scientific research (Bartowitz 2022); (Campbell 2011); (Catanzaro and D'Amato 2019); (B. E. Law, Creating Strategic Reserves to Protect Forest Carbon and Reduce BiodiversityLosses in the United States 2022); (Mildrexler 2020); (Moomaw 2019) clearly indicates that forest management, as practiced today, decreases a forest's capacity to sequester and store carbon. Thinning and logging forests to change wildfire behavior and make wildfire suppression easier is counterproductive. High levels of atmospheric CO2 trigger global warming and a warmer climate is the major factor contributing to more intense and frequent wildfires. Rather than irrationally focusing on a consequence of global warming (i.e., wildfires) it is sensible to directly address one of the chief causes of global warming, high levels of atmospheric CO2. Thus, managing forests for maximum sequestration and storage of C is more reasonable and a better long-term solution to reducing increased wildfire activity.The claim that young trees sequester C more quickly than older trees is used to justify the removal of large, older trees from forests. However, researchers have shown that it is the large, old trees that sequester more C on an annual basis (B. E. Law, Creating Strategic Reserves to Protect Forest Carbon and Reduce Biodiversity Losses in the United States 2022); (Mendelsohn and Sohngen 2019); (Mildrexler 2020); (Wilson 2021); (Moomaw 2019); (Mo 2023); (Hudiburg 2019).After wildfires, forest managers are quick to propose salvage logging to retrieve some of the forest's economic value. Recent research has shown that although salvage logging may recover some economic worth, the activity further damages forest ecosystems, immediately reduces the forest's C storage, reduces any possible C sequestration for decades, is harmful to the soil, degrades forest hydrology, reduces natural regeneration, and harms wildlife habitats and numerous ecosystems (Gunn 2020); (Law and Waring, Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests 2015); (B. E. Law, Creating Strategic Reserves to Protect Forest Carbon and Reduce Biodiversity Losses in the United States 2022).Forest soils have been found to store about half of the C in a forested area. Forest management that focuses on timber extraction disturbs soils to such an extent that soil carbon storage is immediately diminished (Noormets 2015); (Holub and Hatten 2019); (Prescott and Grayston 2023); (James and Harrison, The Effect of Harvest on Forest Soil Carbon - A Meta-Analysis 2016); (James and others, Effects of forest harvesting and biomass removal on soil carbon and nitrogen: Two complementary meta-analysis 2021); (Rabearison 2023); (Zald 2016).Although most forest managers now publicly admit global warming as fact, they continue to neglect accounting for the impact warming has on soil's ability to store C in organic and inorganic layers (Georgiou 2024); (Raza 2024).Also overlooked is a thorough analysis by forest management of the impact from different harvest intensities to mycorrhizal fungi, underground networks that are essential to tree growth and forest health (Prescott and Grayston 2023); (Treseder and Holden 2013); (Song 2015).Often missing from most assessments of logging and thinning projects is consideration for preserving forest biodiversity, including the biodiversity of soil ecosystems that tree growth and carbon sequestration and storage depend upon (Catanzaro and D'Amato 2019); (Mildrexler 2020); (Prescott and Grayston 2023); (Simard 2020); (Buotte 2020); (Mo 2023); (Thom, Theclimate sensitivity of carbon, timber, and species richness covaries with forest age in boreal-temperate North America 2019).Forests evolved with environmental disturbances (i.e., wildfire, insects, disease, wind, changes in climate) and therefore already have an ecological resilience for recovery. Forests do not remain static in response to natural disturbance.

Nevertheless, on-the-ground forest management is often implemented to freeze natural forest succession at a human-desired fixed state. If forests are to reach their full potential to sequester and store carbon, endeavors to halt natural succession are counterproductive and the source of unintended consequences.Research is slowly revealing additional information about forest carbon cycles. Recent developments in that research show that disturbances affect whether forests are C sinks or sources (Law and Waring, Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests 2015); (Wilson 2021); (Dobor 2018); (Thom, Disturbance legacies have a stronger effect on future carbon exchange than climate in a temperate forest landscape 2018).Forest management by assumption related to the carbon consequences of disturbance, especially human caused, permit managers to reach erroneous conclusions (Ghimire 2015); (Stenzel 2021).Current on-the-ground forest-management activities usually involve human disturbances (i.e., logging and/or thinning, prescribed burning, pile burning). Those activities are management response to higher-than-desired levels of insect activity or attempts to change wildfire behavior and/ or to make wildfire suppression easier. However, such activities are ill-informed, harmful to ecosystems, and degrade a forest's C sequestration and storage ability (Baker and Williams 2015); (Bradley 2016); (Bartowitz 2022); (Muller 2016); (Law and Moomaw, Keeping trees in the ground where they are already growing is an effective low-tech way to slow climate change 2021); (B. E. Law, The Status of Science on Forest Carbon Management to Mitigate Climate Change and Protect Water and Biodiversity 2022); (Mildrexler 2020); (Moomaw 2019); (Wilson 2021); (Noormets 2015); (Prescott and Grayston 2023); (Holub and Hatten 2019); (James and Harrison, The Effect of Harvest on Forest Soil Carbon - A Meta-Analysis 2016); (James and others, Effects of forest harvesting and biomass removal on soil carbon and nitrogen: Two complementary meta-analysis 2021); (Campbell 2011); (Simard 2020); (Stenzel 2021).Besides logging and thinning to change wildfire behavior and make wildfire suppression easier, such vegetative treatments are prescribed to reduce tree mortality from mountain pine beetle (MPB) attacks. Recent research reveals that the likelihood of treated areas being attacked by MPBs is minimal and that, if the area is visited by beetles, tree mortality caused by MPB is less than the mortality from logging and thinning (Morris 2023); (Ghimire 2015).Wildfire is the most discussed forest disturbance by far, no doubt because humans have an innate fear of fire, it appears to be haphazard, and, in many cases, the resulting changes are abrupt and easily noticeable.Forest-management activities that include logging and thinning to change wildfire behavior and make wildfire suppression easier, immediately reduce a forest's ability to sequester C, decreasealready stored C, and escalate the transformation of stored C to atmospheric CO_2 (Coulston 2023).Elected officials, the media, and the public mistakenly believe that when a wildfire occurs in a forest, huge amounts of carbon are released to the atmosphere. However, independent researchers have verified that relatively small amounts of a forest's total carbon is released to the atmosphere by wildfire (Law and Moomaw, Keeping trees in the ground where they are already growing is an effective low-tech way to slow climate change 2021); (Law and Waring, Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests 2015); (Wilson 2021).The biomass killed but not consumed during forest fires does release carbon to the atmosphere but slowly enough to remain well within Earth's buffering capacity. Recent research indicates that vegetative treatments to reduce crown fire (i.e., change wildfire behavior) exceed any hopeful gain in carbon sequestration and storage (Law and Waring, Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests 2015); (B. E. Law, Creating Strategic Reserves to Protect Forest Carbon and Reduce Biodiversity Losses in the United States 2022); (Wilson 2021); (Campbell 2011); (Stenzel 2021); (Morris 2023); (Moomaw 2019); (Mildrexler 2020); (Zald 2016). Earth is currently experiencing global warming which causes extreme weather. Although extended periods of drought have happened in the past, a warmer Earth causes more weather extremes, one of which is long periods of drought. Forests that experience extended droughts, undergo ecosystem shifts and changes to plant and animal species. Certain individuals of a tree species survive, others do not as the effects of water shortages accrue. Research reveals that it is the older trees[mdash]the ones typically removed during logging projects[mdash]that are most able to withstand prolonged drought. Forest managers should assume that droughts will stress forests and prepare accordingly by refraining from implementing projects that include the removal of old trees which are also one of the largest carbon stores in a forest (Batllori 2020); (Law and Waring, Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests 2015); (Dobor 2018). There are many claims that the use of wood harvested from forests should be substituted for other building materials (steel and concrete) with higher carbon footprints. Articles written about this subject usually omit portions of the life cycle of wood products and overestimate the willingness of the building industry to adjust to different materials (Law and Waring, Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests 2015); (Hudiburg 2019); (Howard 2021); (Bysouth 2024); (Johnston and Radeloff 2019); (Mishra 2022).Many claims are made that using wood for bioenergy is carbon neutral. Burning wood for energy usually produces more emissions (C) than coal. In addition, recovery of all emissions by future growth takes longer than the age of the harvested forest (Dugan 2018); (B. E. Law, The Status of Science on Forest Carbon Management to Mitigate Climate Change and Protect Waterand Biodiversity 2022); (B. E. Law, Creating Strategic Reserves to Protect Forest Carbon and Reduce Biodiversity Losses in the United States 2022).Even so called "sustainable forest management" does not support the use of wood for bioenergy (Hudiburg 2019); (James and Harrison, The Effect of Harvest on Forest Soil Carbon - A Meta-Analysis 2016).IntroductionIt is widely accepted by the scientific community that Earth is now experiencing global warming. The atmosphere contains increased levels of CO2 never reached during human existence on the planet.Recent research (Xu 2020) reveals that humans have mostly inhabited areas of the planet withing specific temperature ranges (mean annual temperature [sim]11 to 15 C). When temperature ranges shifted because of changes to climate, humans migrated to areas within the preferred range. Now, as Earth continues to warm, humans are already migrating toward the poles and out of areas no longer hospitable.The most effective method of global warming mitigation is to eliminate the use of fossil fuels as soon as possible. But because CO2 is long-lived in the atmosphere, measures must be taken to transfer atmospheric CO2 into long-term carbon (C) storage. Humans have a tendency to address perceived problems by applying additional technology, but such methods are expensive, consume valuable resources, take time to implement, and almost always cause unintended consequences.This paper looks at how changes to forest management would substantially improve the sequestering and long-term storage of carbon without resorting to unproven expensive technology.Substantially more than 200 research articles published since 1960 were reviewed during the preparation of this paper. Because the newer articles reference earlier publications, only the most recent are included as references. (Science is the never-ending, self-correcting, rigorous pursuit of knowledge. Thus, newer research should either reinforce or refute that which came before.)In Western US and Canada, forest management continues to log but now justifies it as necessary to save forests from wildfire and prevent carbon emissions. Such policies may provide politically expedient soundbites, but research does not support logging as a method for maximizing carbon storage and sequestration. (Bartowitz 2022)Climate change has intensified the scale of global wildfire impacts in recent decades. In order to reduce fire impacts, management policies are being proposed in the western United States to lower fire risk that focus on harvesting trees, including large-diameter trees. . . . While the primary goal is fire risk reduction, these policies have been interpretedas strategies that can be used to save trees from being killed by fire, thus preventing carbon emissions and feedbacks to climate warming. This interpretation has already resulted in cutting down trees that likely would have survived fire, resulting in forest carbon losses that are greater than if a wildfire had occurred. . . . We find that forest fire carbon emissions are on average only 6% of anthropogenic FFE (fossil fuel emissions) over the past decade. While wildfire occurrence and area burned have increased over the last three decades, per area fire emissions for extreme fire events are relatively constant. In contrast, harvest of mature trees releases a higher density of carbon emissions (e.g., per unit area) relative to wildfire (150-800%) because harvest causes a higher rate of tree mortality than wildfire. Our results show that increasing harvest of mature trees to save them from fire increases emissions rather than preventing them. Shown in context, our results demonstrate that reducing FFEs will do more for climate mitigation potential (and subsequent reduction of fire) than increasing extractive harvest to prevent fire emissions. Emphasis addedPublic perception and existing overestimates of forest mortality and carbon emissions from wildfire feeds into the misconception that wildfire kills all live forest cover and combusts all forest carbon (Wiedinmyer and Nef 2007; Mater 2017; Zink 2018). The reality of actual fire emissions calculated from mixed-severity combustion rather than overestimates calculated from the false high-severity narrative highlights the need to disentangle ecological impacts of wildfire from societal impacts (i.e., loss of lives and houses). This will help to ensure that risk-reduction solutions can decrease wildfire disasters while still maintaining ecosystem services, such as live tree carbon uptake and wildlife habitat (Kolden 2020).The most effective forest management strategy to protect forest carbon stocks on public lands is to preserve forests through decreased harvest and thinning, lengthened harvest rotations, increased proportion of long-term wood products, reduced harvest and mill waste, and working toward afforestation and reforestation (Hudiburg et al 2013; Law et al 2018; Buotte et al 2020. . . . In western United States forests, 33 to 46% of aboveground live biomass is stored in the large diameter trees (>60 cm; Lutz et al 2018; Mildrexler et al 2020). Carbon-smart treatments on public lands need to be specific about diameter limits to avoid large-diameter tree removal.In practice, large-scale extractive forest management efforts will hamper climate mitigation and may be futile for decreasing fire risk. To be most effective, policy will need to focus on fire-wise adaptations for homes and property and disentangle ecologically-good fire from destructive fires (Kolden 2020). Protecting forests with ecologically sound principles, rather than increasing extractive management, may be the best scenario for the mitigation of climate change (Law et al 2018), and protecting humans, biodiversity, and forests (Walsh et al 2019; Buotte et al 2020; Law et al 2021).It has been recognized that extraction should not be the focus of forest management.Forest management practices that can increase carbon sequestration and storage and reduce emissions include modification of rotation length; avoiding losses from pests, disease, fire, and extreme weather; managing the soil carbon pool; and maintaining biodiversity. (Muller 2016)Research by (Catanzaro and D'Amato 2019) suggest that passive management will provide the greatest amount of carbon storage.Taking a passive approach to forest management will likely provide the greatest amount of carbon storage.The most important carbon consideration of active forest management is the loss of forest carbon storage resulting from the removal of trees. Though some of the trees removed during a timber harvest will end up in long-term forest products, any removal of trees is a temporary reduction in carbon storage on that property and at that time.Published research by (B. E. Law, Creating Strategic Reserves to Protect Forest Carbon and Reduce Biodiversity Losses in the United States 2022) reiterates that extracting forest resources, even grazing, worsens global warming, diminishes biodiversity, and reduces the ability of forests to sequester and store carbon.Our key message is that many of the current and proposed forest management actions in the United States are not consistent with climate goals, and that preserving 30 to 50% of lands for their carbon, biodiversity and water is feasible, effective, and necessary for achieving them.. . ., functionally separating carbon, water, and biodiversity and considering them independently leads to actions that inadvertently reduce the values of each, and can increase carbon emissions.Many current U.S. forest management practices that optimize resource extraction are inconsistent with this scientific consensus, are worsening both climate change and biodiversity loss, and decreasing multiple ecosystem services of U.S. forests. Strategies to mitigate and adapt to climate change have been proposed by scientists (Pandit et al 2021) and policymakers or those implemented by land managers and industries, and recent research has quantified their effectiveness and inadequacies.Mature and old forests generally store more carbon in trees and soil than young forests, and continue to accumulate it over decades to centuries (Law et al 2018; Hudiburg et al 2009; Mildrexler et al 2020) making them the most effective forest-related climate mitigation strategy. . . . Converting mature and older forests to younger forests results in a significant loss of total carbon stores, even when wood products are considered (Hudiburg et al 2019; Harmon and Marks 2019).A reaction to the recent increase in the intensity and frequency of wildfires is to thin forests to reduce the quantity of combustible materials. However, the amount of carbon removed by thinning is much larger than the amount that might be saved from being burned in a fire, and far more area is harvested than would actually burn (Hudiburg et al 2011; Campbell et al 2012; Mitchell et al 2009; Rhodes and Baker 2008; Hudiburg et al 2013). Most analyses of mid- to long-term thinning impacts on forest structure and carbon storage show there is a multi-decadal biomass carbon deficit following moderate to heavy thinning (Zhou et al 2013). . . . Regional patchworks of intensive forest management have increased fire severity in adjacent forests (Hudiburg et al 2013). Management actions can create moresurface fuels. Broad-scale thinning (e.g., ecoregions, regions) to reduce fire risk or severity (Zald and Dunn 2018) results in more carbon emissions than fire, and creates a long-term carbon deficit that undermines climate goals.Instead of regularly harvesting on all of the 70% of U.S. forest land designated as "timberlands" by the U.S. Forest Service, setting aside sufficient areas as Strategic Reserves would significantly increase the amount of carbon accumulated between now, 2050 and 2100, and reestablish greater ecosystem integrity, helping to slow climate change and restore biodiversity.Preserving and protecting mature and old forests would not only increase carbon stocks and growing carbon accumulation, they would slow and potentially reverse accelerating species loss and ecosystem deterioration, and provide greater resilience to increasingly severe weather events such as intense precipitation and flooding.Domestic livestock grazing occurs on 85% of public lands in the western U.S. and is a significant source of greenhouse gas emissions (12.4 Tg CO_2

equivalents per year). Due to overgrazing, it was estimated to decrease aboveground biomass carbon by about 85% when converted from forests and woodlands to grass-dominated ecosystems (Kauffman et al 2022). Discontinuing or greatly reducing this practice would be an important climate mitigation strategy.Maintaining forest ecosystem integrity is "fundamental" to resilient development and climate mitigation and adaptation. Current extractive management practices on all forests designated as "timberlands" are inconsistent with slowing, and eventually achieve lower "atmospheric concentrations of greenhouse gases that will avoid dangerous anthropogenic interference with the climate system" (UNFCC 1992). Many of the existing forest management practices allegedly [to] protect forests and homes from wildfire and are having severe adverse effects on forest ecosystem integrity and resilience, and are worsening climate change and diminishing biodiversity. Forest bioenergy adds significantly more CO2 to the atmosphere than fossil fuels. Its use is based upon a mistaken assumption that it is [more] necessary to shift to renewable energy than to reduce heat-trapping gas emissions such as carbon dioxide, rather than to reduce emissions from all sources including forest bioenergy for electricity.As current forest management strives to reduce the intensity of wildfire using logging and thinning, large and old trees (i.e., Douglas-fir) are often targeted because of their dollar value. Research by (Mildrexler 2020) indicates that removing large, shade-tolerant tree is a strategy which reduces a forest's carbon storage.The rationale for harvesting large trees is premised upon the use of historical baselines of stand structure and species composition as management targets, and assuming that by removing large shade-tolerant species like grand fir and Douglas-fir it will promote resilience to future drought and disturbance (Johnston et al 2018; Merschel et al 2019; Hessburg et al.2020). However, ongoing climate change and many other anthropogenic stressors such as habitat fragmentation, invasive species, and declines in biodiversity,heighten concerns over use of historical conditions as management targets (Millar et al 2007; IPCC 2018; Ripple et al 2020).Carbon storage is an increasingly important management objective for National Forest Lands in the United States (Depro et al 2008; Dilling et al 2013; Dugan et al 2017). . . . Strategies to mitigate climate change effects on forests require careful examination of the tradeoffs of proposed forestry practices on forest carbon stock accumulation, water cycling, and additional environmental co-benefits of forests, such as biodiversity and microclimatic buffering (McKinley et al 2011; Law et al 2018; Sheil 2018; Buotte et al 2020).As others (Catanzaro and D'Amato 2019) have suggested, passive forest management (proforestation) may be the best method for increasing a forest's ability to sequester and store carbon. Continuing current practices[mdash]business as usual (BAU)[mdash]will decrease both. (Moomaw 2019)Climate change and loss of biodiversity are widely recognized as the foremost environmental challenges of our time. Forests annually sequester large quantities of atmospheric carbon dioxide (CO2), and store carbon above and below ground for long periods of time. Intact forests[mdash]largely free from human intervention except primarily for trails and hazard removals[mdash]are the most carbon-dense and biodiverse terrestrial ecosystems, with additional benefits to society and the economy. . . . U.S. forests have the potential for much more rapid atmospheric CO2 removal rates and biological carbon sequestration by intact and/or older forests. . . . , growing existing forests intact to their ecological potential[mdash]termed proforestation[mdash]is a more effective, immediate, and low-cost approach that could be mobilized across suitable forests of all types. Proforestation serves the greatest public good by maximizing co-benefits such as nature-based biological carbon sequestration and unparalleled ecosystem services such as biodiversity enhancement, water and air quality, flood and erosion control, public health benefits, low impact recreation, and scenic beauty.Life on Earth as we know it faces unprecedented, intensifying, and urgent imperatives. The two most urgent challenges are (1) mitigating and adapting to climate change (Intergovernmental Panel on Climate Change, 2013, 2014, 2018), and (2) preventing the loss of biodiversity (Wilson 2016; IPBES 2019).If current management practices continue, the world's forests will only achieve half of their biological carbon sequestration potential (Erb et al 2018); intensifying current management practices will only decrease living biomass carbon and increase soil carbon loss.We conclude that proforestation has the potential to provide rapid, additional carbon sequestration to reduce net emissions in the U.S. by much more than the 11% that forests provide currently (United States Environmental Protection Agency 2019).Although biological carbon storage in managed stands, regardless of the silvicultural prescription, is generally lower than in unmanaged intact forests (Harmon et al 1990; Ford and Keeton 2017)[mdash]even after the carbon stored in wood products is included in the calculation[mdash]stands managed with reduced harvest frequency and increased structuralretention sequester more carbon than more intensively managed stands (Nunery and Keeton

2010; Law et al 2018).Large trees and intact, older forests are not only effective and cost-effective natural reservoirs of carbon storage, they also provide essential habitat that is often missing from younger, managed forests (Askins 2014).. . ., forest managers often justify management to maintain heterogeneity of age structures to enhance wildlife habitat and maintain "forest health" (Alverson et al 1994). . . . Management also results in undesirable consequences such as soil erosion, introduction of invasive and non-native species (McDonald et al 2008; Riitters et al 2018), loss of carbon[mdash]including soil carbon (Lacroix et al 2016), increased densities of forest ungulates such as white-tailed deer (Whitney 1990)[mdash]a species that can limit forest regeneration (Waller 2014)[mdash]and a loss of a sense of wildness (e.g., Thoreau 1862).Forest health is a term often defined by a particular set of forestry values (e.g., tree regeneration levels, stocking, tree growth rates, commercial value of specific species) and a goal of eliminating forest pests. Although appropriate in a commercial forestry context, these values should not be conflated with the ability of intact natural forests to continue to function and even thrive indefinitely and provide a diversity of habitats on their own (e.g., Zlonis and Niemi 2014). Natural forests, regardless of their initial state, naturally develop diverse structures as they age and require from us only the time and space to self-organize (e.g., Larson et al 2014; Miller et al 2016).In 1905 Gifford Pinchot, Chief of the U.S. Forest Service, summarized his approach to the nation's forests when he wrote ". . .where conflicting interests must be reconciled, the question will always be decided from the standpoint of the greatest good of the greatest number in the long run." This ethos continues to define the management approach of the U.S. Forest Service from its inception to the present day. Remarkably, however, even in 2018 the five major priorities of the Forest Service do not mention biodiversity, carbon storage, or climate change as major aspects of its work (United States Forest Service, 2018).. . ., proforestation provides the most effective solution to dual global crises[mdash]climate change and biodiversity loss. It is the only practical, rapid, economical, and effective means for atmospheric CDR (carbon dioxide removal) among the multiple options that have been proposed because it removes more atmospheric carbon dioxide in the immediate future and continues to sequester it long-term. Proforestation will increase the diversity of many groups of organisms and provide numerous additional and important ecosystem services (Lutz et al 2018). Emphasis addedA paper more than a decade ago (Campbell 2011) found that thinning and logging to reduce wildfire emissions and increase C sequestration is not supported by scientific research.It has been suggested that thinning trees and other fuel-reduction practices aimed at reducing the probability of high-severity forest fire are consistent with efforts to keep carbon (C) sequestered in terrestrial pools, and that such practices should therefore be rewarded rather than penalized in C-accounting schemes. . . . Our review reveals high C losses associated with fuel treatment, only modest differences in the combustive lossesassociated with high-severity fire and the low-severity fire that fuel treatment is meant to encourage, and a low likelihood that treated forests will be exposed to fire. Although fuel-reduction treatments may be necessary to restore historical functionality to fire-suppressed ecosystems, we found little credible evidence that such efforts have the added benefit of increasing terrestrial C stocks.. . ., we believe that current claims that fuel-reduction treatments function to increase forest C sequestration are based on specific and sometimes unrealistic assumptions regarding treatment efficacy, wildfire emissions, and wildfire burn probability.The empirical data used in this paper derive from semiarid, fire-prone conifer forests of the western US, which are largely composed of pine, true fir (Abies spp), and Douglas fir. These are the forests where management agencies are weighing the costs and benefits of up-scaling fuel-reduction treatments. Although it would be imprudent to insist that the quantitative responses reported in this paper necessarily apply to every manageable unit of fire-prone forest in the western US, our conclusions depend not so much on site-specific parameters but rather on the basic relationships - between growth, decomposition, harvest, and combustion - to which no forest is exempt. To simply acknowledge the following - that (1) forest wildfires primarily consume leaves and small branches, (2) even strategic fuels management often involves treating more area than wildfire would otherwise affect, and (3) the intrinsic trade-off between fire frequency and the amount of biomass available for combustion functions largely as a zero-sum game - leaves little room for any fuel-reduction treatment to result in greater sustained biomass regardless of system parameterization. Only when treatment, wildfire, or their interaction leads to changes in maximum biomass potential (i.e., system state change) can fuel treatment profoundly influence C storage.On the basis of material reviewed in this paper, it appears unlikely that forest fuel-reduction treatments have the additional benefit of increasing terrestrial C storage simply by reducing future combustive losses and that, more often, treatment would result in a reduction in C stocks over space and time.

Claims that fuel-reduction treatments reduce overall forest C emissions are generally not supported by first principles, modeling simulations, or empirical observations. The C gains that could be achieved by increasing the proportion of large to small trees in some forests are limited to the marginal and variable differences in biomass observed between fire-suppressed forests and those experiencing frequent burning of understory vegetation.A study by (Bysouth 2024), which researched forest management in Canada, found that the reporting of fossil fuel emissions during forest management operations was either ignored or underreported. Minimizing or ignoring the amount of CO2 produced by fossil fuel use during on-the-ground forest-management activities appears to be the norm during project analysis.Recent research has shown forest-related emissions reported in national greenhouse gas inventories are much lower than global estimates from models summarized in Intergovernmental Panel on Climate Change reports.Transparently and accurately reporting GHG emissions from the forestry sector is necessary to inform effective forestry-related policies and nature-based climate solutions (e.g., Drever et al 2021; Moomaw and Law 2023).Notably, this does not include the fossil fuel emissions attributed to the cutting and hauling activities associated with harvest to produce HWPs (Harvested Wood Products).We calculated the net emissions attributed to the forestry sector in the Canadian managed forest from 2005 to 2021 and found that the sector was a sizable net source of emissions to the atmosphere, with annual mean GHG emissions of 90.8 Mt. CO2e.Our analysis demonstrates that the current approach used for accounting forest carbon sinks in Canada may, in part, explain why forest-related emissions reported in national greenhouse gas inventories are much lower than global estimates from models summarized in IPCC reports. More specifically, we demonstrate that Canada's use of the IPCC's natural disturbance provision creates a dubious anthropogenic forest carbon sink that leads to a bias toward underestimating the GHG emissions directly attributable to the forestry sector.If the forestry sector is recognized as a GHG emitter, policies and management approaches could more readily shift to include, for example, strategies such as longer harvest rotations, silvicultural methods that maintain more on-site biomass after harvests, reductions in harvest levels, and a decrease in the production of short-lived forest products.Carbon storage and sequestrationThe assumption is often made that young trees sequester carbon more quickly than older trees and therefore, a forest composed of young trees is preferable for mitigating global warming. Even if the hypothesis is correct, that young trees sequester carbon more quickly than older trees, concluding that removing large, older trees to allow young trees to flourish ignores the fact that a large old tree sequesters more carbon on an annual basis than a young tree. Young trees may grow more quickly but are unable to annually sequester as much carbon as an old tree.A global study of 48 forests of all types found that among "mature multi-aged forests" half the living aboveground carbon was in the largest diameter 1% of the trees (Lutz et al 2018). A study of six National Forests in Oregon found that trees of 53 cm DBH or greater comprised just 3% of the total stems, but held 43% of the aboveground carbon (Mildrexler et al 2020). The U.S. Forest Service decided to drop a restriction on harvesting large trees in this category (Federal Register Document 2021-00804; https://www.govinfo.gov/content/pkg/FR-2021-01-15/pdf/2021-00804.pdf, accessed 20 April 2022), an action at odds with climate and biodiversity goals. Contrary to common belief, older forests continue to accumulate large quantities of carbon in trees and forest soils. Globally, forests older than 200 years continue to accumulate carbon at a rate of 1.6 to 3.2 Mg C ha[minus]1 yr[minus]1. (B. E. Law, Creating Strategic Reserves to Protect Forest Carbon and Reduce Biodiversity Losses in the United States 2022). . . an untouched natural forest would have sequestered even more carbon than the actual forest has. (Mendelsohn and Sohngen 2019)For a forest of young trees to sequester as much carbon per unit of ground area as a mature forest, the density of trees would have to be substantial. But according to most forest managers, a dense forest is primed for disturbance (i.e., insects, disease, and wildfire). A claim of "overly dense forest" is the reason most often used to support vegetation management (i.e., logging and thinning, prescribed fire, pile burning), especially to minimize the consequences of wildfire.Old large trees store large amounts of carbon and continue to sequester huge amounts of carbon for hundreds of years. Research by (Mildrexler 2020) confirms that and shows how important large trees are to a forest's carbon cycle.Large-diameter trees store disproportionally massive amounts of carbon and are a major driver of carbon cycle dynamics in forests worldwide. . . . Large trees accounted for 2.0 to 3.7% of all stems (DBH [ge] 1" or 2.54 cm) among five tree species; but held 33 to 46% of the total AGC stored by each species. Pooled across the five dominant species, large trees accounted for 3% of the 636,520 trees occurring on the inventory plots but stored 42% of the total AGC. . . . Given the urgency of keeping additional carbon out of the atmosphere and continuing carbon accumulation from the atmosphere to protect the climate system, it would be prudent to continue protecting ecosystems with large trees for their carbon stores, and also for their co-benefits of habitat for biodiversity, resilience to drought and fire, and microclimate buffering under future climate extremes.Forest carbon accumulation is crucial for mitigating ongoing climatic change, with individual large trees storing a substantial portion of the overall carbon in living trees. Globally, forests store about 862 Gt carbon in live and dead vegetation and soil, with 42% of it stored in live biomass (above- and below-ground; Pan et al 2011).Large-diameter trees constitute about half of the mature forest biomass worldwide and are key to the ability of forests to accumulate substantial amounts of carbon needed to mitigate climate change (Luyssaert et al 2008; Lutz et al 2018). Trees exceeding 60 cm (23.6 in) diameter at breast height (DBH) comprise [sim]41% of the world's aboveground live tree biomass (Lutz et al 2018). Furthermore, on average, 50% of the live tree biomass carbon in all types of forests globally is stored in the largest 1% of trees, but the value for the United States is lower, [sim]30% in the largest 1% of trees due to widespread historical logging of large trees (Lutz et al 2018). A single large tree can add the same amount of carbon to the forest within a year as is contained in a single midsized tree of the same species (Stephenson et al 2014). The relationship between large-diameter trees and overall forest biomass suggests that forests cannot accumulate aboveground carbon (AGC) to their ecological potential without large trees (Lutz et al 2018). Recognition of the importance of large-diameter trees in determining global atmospheric carbon stocks has led to management recommendations to conserve existing large-diameter trees and those that will soon reach large diameters (Lindenmayer et al 2014; Lutz et al 2018; Moomaw et al 2019).. . . results clearly showed that for large trees, a small increase in diameter corresponds to a massive increase in additional carbon storage relative to a small tree increasing by the same diameter increment. Overall, as trees grow larger, each additional centimeter of stem diameter corresponds with a progressively larger increase in tree carbon storage.Large trees (DBH [ge]21 in or 53.3 cm) constitute [sim]3% of the total stems, but store [sim]42% ([sim]45% with CRM) of the AGC . . . This finding highlights the important role of large trees in storing carbon in eastside forest ecosystems, and is consistent with previous findings on the disproportionately important role of large trees in the forest carbon cycle (Hudiburg et al 2009; Lutz et al 2012, 2018; Stephenson et al 2014). The sharp increase in carbon storage with increasing tree diameter speaks to the importance of preserving mature and old large trees to keep this carbon stored in the forest ecosystem where it remains for centuries (Law et al 2018; Lutz et al 2018). Once trees attain large stature, each additional DBH increment results in a significant addition to the tree's total carbon stores, whereas small-diameter trees must effectively ramp up to size before the relationship between DBH and AGC results in significant carbon gains.Forestry practices exert significant controls on stand structure and forest carbon dynamics, and alterations of harvest practices can substantially alter carbon storage and accumulation (Masek et al 2011; Turner et al 2011; Krankina et al 2012; Kauppi et al 2015; Law et al 2018). Generally, there is a negative relationship between harvest intensity and forest carbon stocks whereby as harvest intensity increases, forest carbon stocks decrease while emissions increase (Hudiburg et al 2009; Mitchell et al 2009; Simard et al 2020). It can take centuries to reaccumulate forest carbon stocks reduced by harvest (Birdsey et al 2006; McKinley et al 2011). . . . The amount of harvested carbon that remains stored in wood products is insufficient to offset the loss of carbon stored in the forest. If harvested, life cycle assessment shows that 65% of the wood harvested in Oregon over the past 115 years has been emitted to the atmosphere, 16% is in landfills and only 19% remains in wood products (Hudiburg et al 2019). Thus, harvesting the large trees will increase, not decrease emissions, and end centuries of long-term carbon storage in the forests.This proforestation strategy is among the most rapid means for accumulating additional quantities of carbon in forests and out of the atmosphere (Moomaw et al 2019).The importance of forest carbon storage is now greatly amplified by a warming climate that must urgently be addressed with reductions in greenhouse gases and natural climate solutions (IPCC 2018; Ripple et al 2020).. . . trees continue to grow, sequestering more carbon into long-term stores (Stephenson et al 2014; Law et al 2018; Domke et al 2020). Older trees ([sim]100 years) are the next generation of old growth and already possess qualities associated with large, old trees, such as large canopies, deep root systems, and thick, fire-resistant bark.The consequences of reducing protection of large trees are significant reduction in forest carbon stores and their climate mitigation, impacts on habitat for animals including birds, and resilience to a changing climate for decades to centuries to come. Given the rarity of large trees across the landscape, and their outsized role in storing carbon removed from theatmosphere, our findings call into question the value of removing large trees for forest modification . . .Research by (Wilson 2021) concurs that old-growth forests store far more carbon than young dense forests.Because larger trees can store exponentially more carbon than smaller trees (Keith et al 2014a, Ximenes et al 2018), forests comprised of a few large trees (such as old growth forest) typically store more carbon than those comprised of many small trees (such as regrowth) (Keith et al 2014a).As many climate scientists assert, not only is it prudent to allow mature and old-growth trees to grow because they store and sequester such large amounts of carbon, research by (Moomaw 2019) proposes that forests should be allowed to grow with little if any human interference.Forests are essential for carbon dioxide removal (CDR), and the CDR rate needs to increase rapidly to remain within the 1.5 or 2.0oC range (Intergovernmental Panel on Climate Change 2018) specified by the Paris Climate Agreement (2015). Growing existing forests to their biological carbon sequestration potential optimizes CDR while limiting climate change and protecting biodiversity, air, land, and water. Natural forests are by far the most effective (Lewis et al 2019).For example, Law et al (2018) reported that extending harvest cycles and reducing cutting on public lands had a larger effect than either afforestation or reforestation on increasing carbon stored in forests in the Northwest United States. In other regions such as New England (discussed below), longer harvest cycles and proforestation are likely to be even more effective. Our assessment on the climate and biodiversity value of natural forests and proforestation aligns directly with a recent report that pinpointed "stable forests" - those not already significantly disturbed or at significant risk - as playing an outsized role as a climate solution due to their carbon sequestration and storage capabilities (Funk et al 2019).. . ., forests' potential carbon sequestration and additional ecosystem services, such as high biodiversity unique to intact older forests, are also being degraded significantly by current management practices (Foley et al 2005; Watson et al 2018). . . . If deforestation were halted, and secondary forests were allowed to continue growing, they would sequester [minus]120 Gt C between 2016 and 2100 or [sim]12 years of current global fossil carbon emissions (Houghton and Nassikas 2018). Northeast secondary forests have the potential to increase biological carbon sequestration between 2.3 and 4.2-fold (Keeton et al 2011). . . ., based on a growing body of scientific research, we conclude that protecting and stewarding intact diverse forests and practicing proforestation as a purposeful public policy on a large scale is a highly effective strategy for mitigating the dual crises in climate and biodiversity . . .The carbon significance of proforestation is demonstrated in multiple ways in larger trees and older forests. For example, a study of 48 undisturbed primary or mature secondary forest plots worldwide found, on average, that the largest 1% of trees [considering all stems [ge]1 cm in diameter at breast height (DBH)] accounted for half of above ground living biomass (The largest 1% accounted for [sim]30% of the biomass in U.S. forests due to larger average sizeand fewer stems compared to the tropics) (Lutz et al 2018). Each year a single tree that is 100 cm in diameter adds the equivalent biomass of an entire 10-20 cm diameter tree, further underscoring the role of large trees (Stephenson et al 2014). Intact forests also may sequester half or more of their carbon as organic soil carbon or in standing and fallen trees that eventually decay and add to soil carbon (Keith et al 2009). Some older forests continue to sequester additional soil organic carbon (Zhou et al 2006) and older forests bind soil organic matter more tightly than younger ones (Lacroix et al 2016).Forestry models underestimate the carbon content of older, larger trees, and it is increasingly clear that trees can continue to remove atmospheric carbon at increasing rates for many decades beyond 100 years (Robert T. Leverett, pers. comm.; Stephenson et al 2014; Lutz et al 2018; Leverett et al under review).Currently, forest carbon storage on a global scale is under the natural potential. Recent research by (Mo 2023) clearly demonstrates that the prevention of deforestation and allowing forest ecosystems to continue to maturity will contribute to a reduction of carbon emissions and an increase in carbon sequestration and storage.At present, global forest carbon storage is markedly under the natural potential, with a total deficit of 226 Gt (model range = 151-363 Gt) in areas with low human footprint. Most (61%, 139 Gt C) of this potential is in areas with existing forests, in which ecosystem protection can allow forests to recover to maturity. The remaining 39% (87 Gt C) of potential lies in regions in which forests have been removed or fragmented. Although forests cannot be a substitute for emissions reductions, our results support the idea (Walker et al 2022; Bastin et al 2019; Lewis et al 2019) that the conservation, restoration, and sustainable management of diverse forests offer valuable contributions to meeting global climate and biodiversity targets.The underlying goal of our analysis was to investigate the impact of human land-use change on forest carbon stocks globally. . . . This analysis revealed a consistent decline in tree carbon density along the anthropogenic degradation gradient across all biomes, evident in both the ground-sourced and the satellite-derived biomass observations.Previous work has suggested that up to 80% of the world's forests are secondary systems that have undergone anthropogenic degradation (Potapov et al 2017). Our models corroborate these findings, revealing a considerable potential for carbon capture in existing forests by allowing these degraded ecosystems to regenerate to maturity. The difference between current and potential ecosystem carbon stocks amounts to 139 Gt C (108-228 Gt C) in existing forests, representing 61% of the total difference when excluding urban and agricultural areas. Of the total 139 Gt, 11 Gt (8%) can be attributed to biomass loss in existing forest plantations, in which restoring diverse ecosystems could lead to further carbon capture. The remaining 128 Gt can be attributed to human degradation in other forest ecosystems. These findings highlight the importance of forest conservation for carbon capture, as ecosystems are allowed to recover to their mature states. It suggests that a substantial proportion of carbon capture can be achieved with minimal land-use conflicts. . . . evidence shows that reductions in harvesting intensity and forest degradation can deliver important climate benefits (Skytt et al 2021) . . . These observations reinforcethe importance of effective forest conservation and management not only in reducing future carbon emissions (Friedlingstein et al 2020; Xu et al 2021) but also in removing carbon that has already been released into the atmosphere.Understanding the potential for carbon storage in natural forests is crucial for comprehending their role in combating climate change. Our combined modelling approach, including ten estimates from this study and nine others from previous studies, allows us to identify the extent of overlap across diverse approaches and increases our confidence about the scale of the forest carbon potential across the globe. We found that total forest carbon storage is, at present, 328 Gt C (model range = 221-472 Gt C) below its full potential. Of this potential, 102 Gt C (69-134 Gt C) exist in urban areas, cropland, and permanent pasture sites, in which substantial restoration is highly unlikely. Yet, a potential of 226 Gt C (151-363 Gt C) is in existing forests and regions with low human pressure. Of this constrained forest carbon potential, 139 Gt C (61%) can be found in regions that are already forested. This highlights that the prevention of deforestation does not only contribute to the reduction of carbon emissions but has large carbon drawdown potential if ecosystems can be allowed to return to maturity.. . ., our estimations are based on recent climate conditions (1979-2013). If fossil fuel emissions continue to rise, the capacity of ecosystems to capture and store carbon will be threatened by climate-change-induced factors such as increasing temperature, drought, and fire risks (Aleixo et al 2019; Pellegrini et al 2018). CO_2 fertilization also has the potential to further change this system (Zhu et al 2016). The dynamic and vulnerable nature of forests underscores the urgency of conserving existing ecosystems to maintain their carbon sink potential . . .Research by (Hudiburg 2019) exposes that, over the last 100 years, logging has reduced western US forest annual carbon sink capacity by [sim]21%, which suggests that forest carbon storage can be more efficient with the proper management emphasis.We find that Western US forests are net sinks because there is a positive net balance of forest carbon uptake exceeding losses due to harvesting, wood product use, and combustion by wildfire. However, over 100 years of wood product usage is reducing the potential annual sink by an average of 21%, suggesting forest carbon storage can become more effective in climate mitigation through reduction in harvest, longer rotations, or more efficient wood product usage. Of the [sim]10,700 million metric tonnes of carbon dioxide equivalents removed from west coast forests since 1900, 81% of it has been returned to the atmosphere or deposited in landfills. Moreover, state and federal reporting have erroneously excluded some product-related emissions, resulting in 25%-55% underestimation of state total CO_2 emissions.Salvage LoggingEven if, as some researchers assert (without verifiable evidence), salvage logging after natural disturbance may have positive impacts on carbon (C) balances by shifting standing dead andlive trees to building materials or biofuels, the near-term cost of transforming C to atmospheric CO_2 is unlikely to be offset by C sequestration for 20 or more years.Krebs et al (2017) similarly found that allowing a hemlock woolly adelgid outbreak to progress without salvaging (in models) resulted in greater net C sequestration and net storage over the long term in the northeastern US. Dobor et al (2019) observed similar modeled outcomes for ecosystem C stocks following salvage harvesting in European Norway spruce (Picea abies) forests. Our results are consistent with these studies representing similar ecosystem dynamics. The overall implication is that salvage harvesting does not necessarily enhance the resilience of forest C stocks without a short-term cost and some risk that stocks will not recover if subsequent disturbances are likely in the near term (i.e., within 20 years). (Gunn 2020)Most salvage operations include the removal of live trees that appear to be damaged, dying, or hazardous. The removal of any live trees during salvage reduces both C storage, existing sequestration capacity, and may negatively affect forest regeneration.In ponderosa pine forests, moderate severity fire killed only 34% of the trees larger than 20 cm in diameter, . . . Physiological measurements and tree cores shows(sic) many of these trees remain alive and productive 10 years after fire (Irvine et al 2007;

Waring 2005; Becker, 2012), whereas standard surveys led to overestimation of mortality and a policy of removing healthy trees that could serve as shade or aid seedlings by hydraulically redistributing water from deep in the soil (Brooks et al 2002). Removal of surviving trees reduces carbon storage, and adversely impacts regeneration in many cases. (Law and Waring, Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests 2015)Post fire salvage logging is harmful to soil, hydrology, natural regeneration, and wildlife habitats. Salvage logging after disturbance damages natural ecosystems which were modified by the original disturbance.Post-fire harvest and felling of live and dead trees can harm soil integrity, hydrology, natural regeneration, slope stability, and wildlife habitat (Bescha et al 1995). Large standing dead, live yet possibly dying, and downed trees help forests recover and provide habitat for more than 150 vertebrates in the PNW (Rose et al 2001). (B. E. Law, Creating Strategic Reserves to Protect Forest Carbon and Reduce Biodiversity Losses in the United States 2022)In burned watersheds, post-fire logging worsens conditions that have resulted from a century of human activity (Thorn et al 2018; Karr et al 2004) and impedes the rate of recovery. In sum, post-fire treatments can cause a significant loss of ecosystem services (Beschta et al 2004). (B. E. Law, Creating Strategic Reserves to Protect Forest Carbon and Reduce Biodiversity Losses in the United States 2022)Forest SoilWith its historical focus on trees, forest management does little more than pay lip service to the importance of forest soils. The consequence of management's attention being directedelsewhere (i.e., above ground), is that soil in managed forests may be in deficit. (Noormets 2015)According to the current paradigm of soil C dynamics (Sollins et al 1996; von Lutzow et al 2006), the longevity and stability of organic matter in soil is determined by physical accessibility, stabilizing interactions with minerals, and chemical recalcitrance.The C losses are compounded by disturbances associated with management activities and shorter rotation lengths. As a result, the soils in managed forests could be in greater C deficit than those in unmanaged forests, . . .Given that soil is the foundation of forest ecosystems and approximately half of forest C is stored in soil, continuing management focus on harvesting trees overlooks the importance of what happens belowground in forested areas. Not only does the intensity of tree harvest influence belowground ecosystems, but it also determines the effectiveness of forest regeneration.Forest soils generally store around half, or more, of the total carbon in a forest with live and dead trees containing the rest (Birdsey 1992; Turner et al 1995). (Holub and Hatten 2019)Although soil is recognized as the foundation of the forest ecosystem (Kimmins 2003), forestry policies for soil protection in many jurisdictions are still limited to preventing erosion and compaction of soil, and retaining some woody debris on the surface. Soil organic matter (SOM) content is a key property of soils, influencing fertility, water retention and site productivity. SOM is also a critical store of C containing more C than the atmosphere and vegetation combined (Scharlemann et al 2014). Forest soils contain more than 40 % of the total organic C in terrestrial ecosystems (IPCC, 2007; Wei et al 2014). Soil C stocks comprise about 70 % of the ecosystem C stock in the boreal forest, 60 % in temperate forests and 30 % in tropical forests (Pan et al 2011). Soils also harbour an estimated one quarter of the earth's biodiversity (Wagg et al 2019), with millions of species and billions of individual organisms living belowground within a single ecosystem (Bardgett and van der Putten 2014). The taxonomic diversity of soil organisms in terrestrial ecosystems is several orders of magnitude greater than that of aboveground organisms on a per-area basis (Bardgett 2005; Parker 2010). This complex and diverse belowground ecosystem is responsible for the many ecosystem functions and services delivered by healthy soils (de Graaff et al 2015; de Vries et al 2013; Bardgett and van der Putten 2014; Crowther et al 2019). Soil communities include plant roots and associated mycorrhizal fungi, microorganisms such as bacteria, archaea, and fungi, and fauna across a wide range of sizes and trophic groups, linked together in complex food webs (Nielsen et al 2015). This belowground ecosystem is fueled by plant residues from both above- and belowground and from recent plant photosynthate delivered from living root systems (Wardle et al 2004; Pollierer et al 2007). (Prescott and Grayston 2023)Clear-cut harvesting alters soil carbon cycling by cutting off the supply of root and litter inputs. Furthermore, the action of clearing aboveground biomass disturbs the soil surface, increases soil temperature, and alters soil moisture (Londo et al 1999), which tends toincrease heterotrophic respiration rates (Londo et al 1999; Pietikainen et al 2005). (Holub and Hatten 2019)Compared with 20-year recovery periods assumed by many models (Buchholz, T. et al (2014), our results indicate that soil C recovery takes place over at least triple that time frame for both O horizons and mineral soil in many cases. (James and Harrison, The Effect of Harvest on Forest Soil Carbon - A Meta-Analysis 2016)We analyzed 945 studies from 112 publications to examine the effect of harvest on forest soil C around the globe.

There is a significant overall reduction in forest soil C following harvest that occurs in both the O horizon and mineral soil. Significant variation in the response to harvesting was observed among different soil depths, among soil orders, between overstory forest types, and between different harvest intensities and pretreatment strategies. Broadcast burning, in particular, appears to exacerbate loss of soil C in both organic and mineral horizons following harvest. The recovery period of soil C following harvest depends upon soil type and takes at least 60 years in many production forests. One of the most important findings of this analysis is a significant loss (-17.7%) of soil C following harvest in very deep soil (60-100+ cm). Deep layers of the soil are greatly under-represented in the literature, and consequently, there is great uncertainty around this estimate. Examination of deep soil horizons in existing manipulative forest studies, in new studies, and in C inventory should be a clear objective for future research. (James and Harrison, The Effect of Harvest on Forest Soil Carbon - A Meta-Analysis 2016). . ., the environmental impacts of removing forest residues from forestlands have not been well quantified in life-cycle analyses. In fact, forest residues can increase wood decay rates in the mineral soil (Page-Dumroese et al 2021) or on the soil surface (Fin[eacute]r et al 2016), providing important ecosystem services such as maintaining site productivity (McKinley et al 2011), minimizing erosion (Berhe et al 2018), and preserving forest diversity (Attiwill and Adams, 1993; Buchholz et al 2014). Forest residues also play a key role in the carbon cycle in forest soils, resulting in the storage of significant quantities of soil C (Achat et al 2015). As a result, harvesting forest residues for bioenergy or biofuel could have long-term impacts on soil C, potentially reducing the net benefit of GHG offsets. (James and others, Effects of forest harvesting and biomass removal on soil carbon and nitrogen: Two complementary meta-analysis 2021)One of the connections between the above- and below-ground ecosystems is tree roots. (Prescott and Grayston 2023) explain the connection and its complexities.An estimated half of the carbon fixed by trees is transported belowground, a portion of which is exuded into the soil where it fuels a complex belowground food web. The biological transformation of exudates into microbial metabolites and necromass is a major source of soil organic matter (SOM), including persistent mineral-associated organic matter (MAOM). Recent recognition of the fundamental importance of these inputs from living roots for sustaining life below ground and replenishing SOM demands a rethinking of how we harvest forests. By severing the lifeline of living roots, clearcut harvesting devastates much of the belowground biodiversity in forests, and prohibits a principal pathway through which SOM and C stocks are replenished. Retention harvesting retains the influence ofliving roots within retention patches and potentially throughout the harvested area, but only if inter-tree distances are 15 m or less. Retention trees sustain and support the re-establishment of belowground life and function following forest harvest and may mitigate post-harvest soil C losses. Sustaining the belowground ecosystem via inputs from living roots is an underappreciated benefit of continuous-cover and retention forestry.Organic compounds exuded from living roots and associated mycorrhizal fungi are essential for soil biodiversity. Although leaf litter was long assumed to be the principal fuel for the belowground ecosystem, it is now evident that a substantial fraction of soil biota are [sic] directly dependent on recent photosynthate from the tree canopy (H[ouml]gberg et al 2010; Chomel et al 2019). . . . , in a mature temperate forest in Switzerland in which trees were labelled with 13C-depleted CO2, the label was found in most soil invertebrates (earthworms, chilopods, gastropods, diplurans, collembolans, mites and isopods), indicating that most soil invertebrates obtain carbon from living roots, probably via mycorrhizal fungi (Pollierer et al 2007). In contrast, only juvenile millipedes obtained most of their C from leaf litter. In a boreal pine forest, H[ouml]gberg et al (2010) found that C from tree photosynthesis was transferred through roots within a few days and then rapidly distributed through the mycorrhizal fungal mycelium to the soil food web.Mucilage and exudates from living roots and associated mycorrhizal hyphae also facilitate formation of microaggregates (Six et al 2004), and entangle soil particles thereby contributing to the formation of macroaggregates and preventing soil loss through water or wind erosion (Jastrow et al 1998; Six et al 2004; Stokes et al 2009).Bacteria produce extracellular polymeric substances composed mainly of polysaccharides, proteins, and DNA, that generate the biofilm in which they live (Costa et al 2018; Cai et al 2019). These substances stick to mineral or organic particles, roots and fungal hyphae, and glue materials together in aggregates, which can increase the persistence of the organic matter. A considerable amount of SOM, including the more persistent MAOM (mineral-associated organic matter), is derived from C released by living plant roots or associated mycorrhizal fungi and processed by microbial communities on or near their surfaces. Inputs from living roots were 2-13 times more efficient than litter inputs in forming both slow-cycling, mineral-associated SOM and fast-cycling, particulate SOM (Sokol et al 2019). Emphasis addedSoil organic carbon (SOC) is usually higher in the upper soil layers and varies between soil under tree canopy and open areas. Research by (Rabearison 2023) suggest that deep soil may also contribute to C storage. Tree roots may play a significant role in SOC storage.SOC concentration in the upper soil horizons, where organic matter inputs from leaf litter and roots are more abundant, is generally greater than in deeper soil layers (Howlett et al 2011; Moreno et al 2005). However, the deep soil can also contribute significantly to C storage due to their high storage capacity and their importance on long-term C stabilization via interactions with the soil mineral phase (Rumpel and K[ouml]gel-Knabner 2011). . . ., SOC stock was greatest underneath the tree canopy and decreased with distance in an oak forest of central-western Spain due to the fact that tree canopy contributes to litter inputs(Howlett et al 2011). However, others also found that SOC stocks do not always differ with distance from trees (Oelbermann and Voroney, 2007; Peichl et al 2006).SOC storage is determined in part by the balance between C inputs from above- and belowground biomass and root exudates against C losses through microbial decomposition, root respiration and leaching (Epron et al 2006; Mart[iacute]-Roura et al 2019; Schmidt et al 2011).Our results also suggest that tree roots could play a significant role in SOC storage, especially in the deeper soil horizons.Because it influences productivity, understanding soil texture is important for forest management.After harvest history and climate, soil texture (fraction of clay) was important in analyses for both young managed and old unmanaged forests. Many soil physical characteristics (i.e., soil depth, texture, water holding capacity, etc.) influence forest productivity (Binkley and Fisher, 2012; Meyer et al 2007), and these characteristics vary with topographic position (Tromp-van Meerveld and McDonnell, 2006; Griffiths et al 2009). (Zald 2016)Research by (Georgiou 2024) emphasizes that recognition of the interaction of soil to climate is essential.We find that the climatological temperature sensitivity of particulate carbon is on average 28% higher than that of mineral-associated carbon, and up to 53% higher in cool climates.Soil organic C stocks are known to broadly decrease with increasing temperature across climate gradients (Koven et al 2021; Doetterl et al 2915; Jobb[aacute]gy and Jackson 2000). However, the magnitude of this climatological temperature sensitivity can vary across soils (Hartley et al 2021). Indeed, this relationship appears to be modulated by clay and silt content, where fine-textured soils (that is, soils containing higher amounts of clay and silt minerals) have a lower climatological temperature sensitivity compared with coarse-textured sandy soils.Furthermore, most ESMs (Earth system models) tend to underestimate the climatological temperature sensitivity of unprotected C in cool climates, potentially leading to an underestimation of C losses from these unprotected pools with warming, an underestimation of the global carbon cycle-climate feedback and compounding projections of higher productivity-driven C accumulation in these regions.In a recent study, (Raza 2024) provides important information about the two C reservoirs in soil; organic (SOC) and inorganic (SIC).SIC is a long-lived soil C pool with a turnover rate (leaching and recrystallization) of more than 1000 years in natural ecosystems, . . .Inorganic C as soil carbonate (2255 Pg C down to 2 m depth) and as bicarbonate in groundwater (1400 Pg C) together surpass SOC (2400 Pg C) as the largest terrestrial C pool (Monger et al 2015). . . . Carbonate-containing soils account for approximately 50 % of the Earth's ice-free land area and approximately 9 billion hectares of arable land worldwide (Marschner 1995; Lal 2009). Generally, SOC (soil organic carbon) and SIC (soil inorganiccarbon) are inversely related (Lal et al 2021). In humid regions, SOC is higher than SIC. Arid regions account for an estimated 78 % of the global SIC, semiarid for 14 %, and humid regions less than 1 % (Eswaran et a 2000). Emphasis addedThe SIC pool is larger than the atmospheric CO2 pool or terrestrial plant biomass C. It is often assumed that SIC changes very slowly over geological time scales because its contribution to biological cycles is much lower than SOC (Schlesinger 1985). Many recent studies, however, report that SIC is far from stable and can be vulnerable to land use changes and intensive crop production, soil acidification, and water flow and recharge - processes that can reduce and even deplete SIC stocks within a few decades (Khokhlova and Myakshina 2018; Raza et al 2020; Raza et al 2021; Kim et al 2020; Zamanian et al 2018). . . ., SIC losses have irreversible and unpredictable implications for soil health, food security and climate amelioration (Wang et al 2021; Raza et al 2021). . . Soil inorganic C is a major player in the global C cycle and climate change, whose contributions are mainly by releasing CO2 in the atmosphere, that must be understood to achieve mitigation goals related to global land use and climate change.The SIC pool - which is approximately three times larger than the atmospheric C pool (i.e., CO2) - is an overlooked player in the C cycle over human lifetime scales.. . ., this high SIC stability and the assumed negligible contribution of SIC to the global C cycle is true only in natural ecosystems and for fully developed soils - in which the SIC stock is at a steady state equilibrium.Once lost, however, SIC stocks cannot recover within the human lifetime scale because the formation of pedogenic carbonate requires the availability of cations such as Ca^{2+} and Mg^{2+} combining with bicarbonate ions (HCO_3^-) under favorable climatic conditions (precipitation < potential evapotranspiration) (An et al 2019; Dang et al 2022; Liu et al 2023). This makes SIC an irrecoverable C source (Zamanian et al 2021).Neglecting SIC precludes a comprehensive understanding of the global C cycle that hinders the development of effective climate change mitigation strategies. To gain a comprehensive understanding of the global C cycle and to develop effective climate mitigation policies, it is imperative to expand research efforts to include SIC.Widespread assumptions that only surface soil reacts to forest management[mdash]soil equilibrium is reached approximately 20 years after harvest[mdash]and ignoring what happens to soil carbon[mdash]especially to mineral soil[mdash]during forest management, erroneous conclusions are reached regarding the length of time required for the C payback period.. . ., soil C is an essential component of forest C accounting, yet many models assume that only surface soil responds to forest management and that soil C returns to equilibrium within 20 years after harvest (Buchholz et al 2014). Recent national or global assessments of forest C lack any mention of mineral soil C (Ryan et al 2010; McKinley et al 2011; Fahey et al 2010), implicitly assuming that soil C remains constant after forest harvest. Furthermore, carbon monitoring programs include soil C inconsistently. . . ., in a model of the forest C pool change following intensive bioenergy harvest, Zanchi et al (2012) show that the inclusion of soil increases the C payback period by approximately 25 years whensubstituting forest bioenergy for coal. (James and Harrison, The Effect of Harvest on Forest Soil Carbon - A Meta-Analysis 2016)Mycorrhizal FungiResearch by (Prescott and Grayston 2023) found that mycorrhizal fungi play an important role in moving carbon from plants to soil.Mycorrhizal fungal mycelia are another substantial source of SOM in forest soils (Godbold et al 2006; Clemmenen et al 2013; Brabcov[aacute] et al 2016). Annual C inputs from mycorrhizal hyphae in forests range from 1228 to 6890 g C/m^{-2} y^{-1} (Cotrufo and Lavallee 2022). Estimates of mycelial biomass for ectomycorrhizal (ECM) fungi typically range from 100 to 600 kg ha^{-1} (Brabcov[aacute] et al 2016) and estimated turnover rates of mycorrhizal mycelia are 0.3-1.1 $month^{-1}$ (See et al 2022), so input rates of residues of mycorrhizal external mycelia may be in the order of 1 t ha^{-1} y^{-1}. In a poplar plantation, 62 % of C entered the SOM pool via arbuscular mycorrhizal (AM) mycorrhizal mycelia, which exceeded inputs via leaf litter and fine-root turnover (Godbold et al 2006).An estimated 10-44 % of photosynthetically fixed carbon is released by roots or transferred to mycorrhizal fungi (Bais et al 2006; Pausch and Kuzyakov 2018). . . . Release from living roots and mycorrhizal fungi may therefore be a major conduit for C flow throughout the upper soil. H[ouml]gberg et al (2008) estimated that half or more of the soil activity in boreal forests is driven by photosynthate that is transported to mycorrhizal fungi and root-associated microbes within a few days of being fixed.Not only do mycorrhizal fungi move carbon into soil, but they also help plants access soil nutrients, thereby allowing the plants to grow more quickly.Mycorrhizal fungi form symbioses with most plant roots, helping the plants to take up nutrients from soil. As a result, plants that are colonized by these fungi often grow much faster (Hoeksema et al 2010). Essentially, the fungi augment the removal of atmospheric C02 by their plant hosts. A portion of that carbon is then allocated to the mycorrhizal fungi, which use it to build hyphae that extend into the soil (Allison 2006). Once these hyphae die, the carbon in their tissues could be quickly decomposed by other soil microbes, or it could remain in the soil for years to decades. The longer the mycorrhizal carbon remains in the soil, the greater the potential contribution to soil carbon sequestration. (Treseder and Holden 2013)Another group of researchers (Song 2015) revealed that mycorrhizal fungi can transfer carbon and stress signals between plants, even those of a different species. The ability to relay stress signals may prove to be important as Earth continues to warm.We found that mycorrhizal networks transferred physiologically significant levels of photosynthate-derived C and transmitted interspecific stress signals that elicited defense responses in ponderosa pine following manual and insect defoliation of interior Douglas-fir. These results show that mycorrhizal networks are mediators of interactions among trees of different species and defoliators, and therefore likely play a critical role in the defenseresponse and recovery of forests from either abiotic damage or insect outbreaks. The direct pathway of carbon and stress signal transfer through mycorrhizal networks to interspecific plant targets may facilitate shifts in forest composition predicted with climate change.Our research shows that mycorrhizal networks are positioned to play important roles in facilitating regeneration of migrant species that are better adapted to warmer climates and primed for resistance against insect attacks. These results point to the importance of conservation practices maintaining all of the parts and processes of these highly interconnected forest ecosystems to help them deal with new stresses brought by our changing climate.Work by (Treseder and Holden 2013) revealed that some soil carbon compounds were produced not by plants but by fungi and microbes. The same study showed that by improving plant growth, mycorrhizal fungi may determine how much carbon is deposited in soil.Recent work indicates that the carbon compounds that remain in the soil over the long term have been produced by fungi and other microbes, not by plants (Prescott 2010). These microbially derived compounds are extremely diverse and are thus difficult for decomposers to target (Allison 2006). They can include remnants of cell walls, such as chitin, glucans, peptidoglycans, or polysaccharides (Paul and Clark 1996). Microbial residues react with one another and with other components of the soil to form materials that cannot be easily converted to C02.. . ., the extent to which mycorrhizal fungi improve plant growth can also determine how much carbon is deposited in the soil via dead plant material. It is the sum of these three processes[mdash]deposition of mycorrhizal residues, decomposition by mycorrhizal fungi, and augmentation of plant growth[mdash]that determines how mycorrhizal fungi affect carbon storage.BiodiversityForests with sufficient levels of species and structure increase the ability of the forest to withstand disturbances. Striving for biodiversity should not be limited to trees but to all species above- and below-ground. Typical forest management focuses first on trees, second on aboveground species (especially game animals), a distant third on above-ground ecosystems, and only then, if at all, on below-ground species and ecosystems. That emphasis on trees hampers the recognition and acknowledgement of important information. Forest-management activities based on insufficient knowledge typically results in unintended consequences.Forests with diverse species and structure increase forest resiliency by reducing the risk that a disturbance will kill all the trees in a forest because the trees are all the same species or a similar size. In addition, forests with these diverse conditions contain multiple mechanisms for recovery following such events, which will allow for carbon levels to return to pre-disturbance levels more quickly. (Catanzaro and D'Amato 2019)Forest management logging and thinning projects based on a top-down philosophy (i.e., the removal of the largest and oldest trees) result in the unintended consequence of reducingbiodiversity whereas management projects designed to conserve high carbon forests preserve biodiversity. Research by (Mildrexler 2020) shows the benefits of management projects focused on carbon storage and sequestration.In addition to comprising a substantial portion of forest carbon storage and accumulation, large-diameter trees fulfill a variety of unique ecological roles such as increasing drought-tolerance, reducing flooding from intense precipitation events, altering fire behavior, redistributing soil water, and acting as focal centers of mycorrhizal communication and resource sharing networks (Bull et al 1997; Brooks et al 2002; Brown et al 2004; Luyssaert et al 2008; Beiler et al 2015; Lindenmayer and Laurance, 2017). In the United States Pacific Northwest (PNW), carbon dense old growth forests buffer against increasing temperatures by creating microclimates that shelter understory species from rising temperatures (Frey et al 2016; Davis et al 2019a). Forests with large-diameter trees often have high tree species richness, and a high proportion of critical habitat for endangered vertebrate species, indicating a strong potential to support biodiversity into the future and promote ecosystem resilience to climate change (Lindenmayer et al 2014; Buotte et al 2020).High carbon conservation-priority forests support important components of biodiversity and are associated with increased water availability (McKinley et al 2011; Perry and Jones, 2016; Berner et al 2017; Law et al 2018; Buotte et al 2020). Large-diameter snags persist as standing snags for many years, providing valuable wildlife habitat, and account for a relatively high proportion of total snag biomass in temperate forests (Lutz et al 2012). . . . Downed hollow logs continue to serve as important hiding, denning, and foraging habitat on the forest floor (Bull et al 1997; Bull et al 2000). Large decaying wood influences basic ecosystem processes such as soil development and productivity, nutrient immobilization and mineralization, and nitrogen fixation (Harmon et al 1986).Water availability and microclimatic buffering are also disproportionately affected by large trees and intact forests (Frey et al 2016; Buotte et al 2020). Forest canopies of the PNW buffer extremes of maximum temperature and vapor pressure deficit, with biologically beneficial consequences (Daviset al 2019a). Removal of large trees quickly leads to a large increase in soil and canopy heating, which increases enough to impact photosynthesis (Kim et al 2016), seedling survival, and regeneration (Kolb and Robberecht, 1996; Davis et al 2019b). The climatic changes toward warmer and drier conditions expected in the next decades will likely increase forest stress and mortality (Allen et al 2015). . . . Projections suggest that proportionally, the largest changes in microclimatic buffering capacity will occur in lower elevation or dry forests, which currently have more limited buffering capacity (Davis et al 2019a). In these drier regions, microclimatic buffering by forest canopies may create important microsites and refugia in a moisture-limited system (Meigs and Krawchuk, 2018). . . . The bigger trees rarely reach 80% loss of hydraulic conductivity, and both mature pine and mesic Douglas-fir were better buffered from the effects of drought on photosynthesis compared with young pine ([sim]20-year-old) due to full root development and larger stem capacitance in older trees (Kwon et al 2018). . . . While large tree composition may have shifted today relative to European settlement times, these large trees nonetheless continue to perform important functional attributes related to water and climate such as carbon storage, hydraulic redistribution, shielding the understory fromdirect solar radiation, and providing wildlife habitat. These functional attributes of large trees, irrespective of species, characterize ecosystems through thousands to millions of years (Barnosky et al 2017), and are not quickly replaced.Harvest intensity threatens species diversity and richness with clear-cut logging being the biggest threat to biodiversity, especially soil biodiversity.Clear-cut harvesting has profound negative effects on soil biodiversity, which can be minimized by retaining at least half of the living trees during [harvest]. Retaining about 50 % of pre-harvest basal area also maintains pre-harvest levels of other organisms, including plants, lichens, bryophytes, mushrooms, arthropods, birds, and small mammals (Fenton et al 2013; de Groot et al 2016; Fedrowitz et al 2014). (Prescott and Grayston 2023)Species diversity and richness declined with harvesting intensity across the entire climatic gradient, . . . Losses in diversity and richness were lowest in the large patch retention treatment and increased with reductions in residual tree basal area, . . . Where conservation of forest-adapted plant diversity and richness is a high priority in managed forests, our results show that partial cutting with high canopy retention is the most successful strategy to meet this objective across Douglas-fir forests. (Simard 2020)Forest management can play a part in mitigating global warming. Research by (Buotte 2020) asserts forest management should include considerations of biodiversity and carbon storage and sequestration.Here, we identify forests in the western conterminous United States with high potential carbon sequestration and low vulnerability to future drought and fire, as simulated using the Community Land Model and two high carbon emission scenario (RCP 8.5) climate models. High-productivity, low-vulnerability forests have the potential to sequester up to 5,450 Tg CO_2 equivalent (1,485 Tg C) by 2099, which is up to 20% of the global mitigation potential previously identified for all temperate and boreal forests, or up to [sim]6 yr of current regional fossil fuel emissions. Additionally, these forests currently have high above- and below-ground carbon density, high tree species richness, and a high proportion of critical habitat for endangered vertebrate species, indicating a strong potential to support biodiversity into the future and promote ecosystem resilience to climate change.Forest management (e.g., land preservation, reduced harvest) can contribute to climate change mitigation and the preservation of biodiversity (MEA 2005).Biodiversity metrics also need to be included when selecting preserves to ensure species-rich habitats that result from frequent disturbance regimes are not overlooked. The future impacts of climate change, and related pressures as human population exponentially expands, make it essential to evaluate conservation and management options on multi-decadal timescales, with the shared goals of mitigating committed CO_2 emissions, reducing future emissions, and preserving plant and animal diversity to limit ecosystem transformation and permanent losses of species.A recent research article illustrates the benefit of biodiversity on forest ecosystem productivity.Given the positive effect of biological diversity on ecosystem productivity (Liang et al 2016; Veryard et al 2023) the magnitude of the estimates presented here can only be achieved in ecosystems that support a natural diversity of species. Indeed, almost half of global forest production can be directly or indirectly attributed to the role of biodiversity (Liang et al 2016), highlighting that the full carbon potential cannot be achieved without a healthy diversity of species. (Mo 2023)An oft-repeated mistake is the assumption that biodiversity is, or at least should be, static. Forest-management activities to freeze, restore, or establish a "desired" or "past" population of single or multiple species is usually an error based on human-centric reasoning. Research by (Thom, The climate sensitivity of carbon, timber, and species richness covaries with forest age in boreal-temperate North America 2019) suggests that biodiversity will naturally change with forest age.Ecosystem services and biodiversity change over time as boreal-temperate forests undergo processes of stand development. Although there were no common trends in the trajectories of TEC (total ecosystem carbon), timber growth, and species richness in relation to forest age, their combined performance was highest in older forests. . . ., our data suggest that the increase in deadwood occurs concurrently with increases in ALC (aboveground live carbon), which is a much larger carbon pool than deadwood in our study system (e.g., up to an order of magnitude larger in 200-year-old forests). . . . Although decomposition gradually releases carbon to the atmosphere via respiration, the large accumulations of deadwood and litter in old forests also contribute to organic matter and free carbon incorporation into the humus layer and soil profile, thereby increasing belowground carbon pools (Manzoni & Porporato 2009). Emphasis addedTotal species richness was insensitive to forest age overall but followed a unimodal hump-shaped curve instead of the expected U-shaped curve. The pattern was driven by the increase in the number of tree and lichen species during the first decades, while vascular plant species richness decreased with forest age. On the one hand, this finding supports the notion that biodiversity change during forest development strongly depends on the species or taxonomic groups studied (Thom et al 2017; Thorn et al 2017). For instance, rare lichen species are often associated with old-growth forest conditions (Selva 1994) and are used as indicators of forest health (McCune 2000). The overall species richness derived here may thus represent only one aspect of biodiversity within forest landscapes and conservation strategies.DisturbancesSeeking to learn more about carbon cycles, scientists attempt to quantify how carbon transfers from one form to another in forest ecosystems.An objective of carbon cycle science is to quantify transfers of carbon from the atmosphere into live biomass, and to follow the transformation into dead biomass and eventually through the decomposition process to where carbon dioxide is emitted to the atmosphere. Drought-related mortality, fires, and insect outbreaks speed up the rates that carbon is transferred through the cycle, and all of these natural disturbances vary in intensity, spatial extent and patchiness. (Law and Waring, Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests 2015)Disturbance plays an important role in determining whether forests are carbon sinks or sources. Logging and wildfire are common widespread disturbances known to significantly reduce carbon stocks in carbon rich forests, . . . (Wilson 2021)Research by (Dobor 2018) found that disturbances affect the loss of forest carbon in different ways.Our results indicated that the recovery of the pre-disturbance C stocks (C payback time) was reached 17 years after the end of the disturbance episode. The C stocks of a theoretical undisturbed development trajectory were reached 30 years after the disturbance episode (C sequestration parity). Drier and warmer climates delayed simulated C recovery. Without the fertilizing effect of CO_2, C payback times were delayed by 5-9 years, while C parity was not reached within the 21st century. Recovery was accelerated by an enhanced C uptake compared to undisturbed conditions (disturbance legacy sink effect) that persisted for 35 years after the disturbance episode. Future climate could have negative impacts on forest recovery and thus further amplify climate change through C loss from ecosystems, but the effect is strongly contingent on the magnitude and persistence of alleviating CO_2 effects.Most forest ecosystems are able to recover from major perturbation within decades to half-centuries (Jones and Schmitz 2009). However, legacies of forest disturbance events can persist considerably beyond this time frame, and range from altered forest understorey (Bace et al 2017), to modified stand structure (Seidl et al 2014a) and the associated susceptibility to subsequent disturbance (Janda et al 2017).Previous research has indicated that disturbances can alter trajectories of forest C in diverse ways (Bradford et al 2012; Liu et al 2011b) and that it might take decades to recover disturbance-related C losses. Consistent with empirical research, our simulation study showed that a severe disturbance might turn a forest landscape into a net C source, and that it takes several decades to compensate for the C loss from disturbance. We identified CO_2 fertilization as a prominent driver facilitating recovery in a temperate forest landscape. Drier and warmer climate, on the other hand, could slow down the recovery processes under climate change. We also corroborated the presence of an enhanced C sink following disturbance.Forest-management activities are often implemented based on the assumption that a disturbed area will quickly experience another disturbance. But research by (Thom, Disturbance legacies have a stronger effect on future carbon exchange than climate in a temperate forest landscape 2018) indicates that although disturbances decrease a forest's stored carbon, the same forested area is unlikely to be impacted by two consecutive disturbances.Both natural and anthropogenic disturbances have decreased the amount of carbon currently stored in forest ecosystems (Erb et al 2018; Goetz et al 2012; Harmon et al 1990; Seidl et al 2014a). The legacy effects of past disturbances have the potential to significantly influence forest dynamics and alter the trajectories of carbon uptake in forest ecosystems over time frames of decades and centuries (Gough et al 2007; Landry et al 2016; Seidl et al 2014b).. . ., our analysis revealed a low probability for the same area to be affected by the two consecutive disturbance episodes.Forest management has a long history of "management by assumption." Assumptions regarding the carbon consequences of disturbances have a direct impact on management activity design. Assessing the consequences of disturbances without a factual basis permits management to reach erroneous conclusions and trigger unintended consequences.Assessing the long-term future carbon consequences of forest disturbances is highly sensitive to assumptions about recovery rates, with the possibility of slow or no recovery of forest carbon stocks. (Ghimire 2015)The long-term, regional carbon balance effect of forest disturbances is also highly sensitive to changes in disturbance rates. (Ghimire 2015)Analysis by (Stenzel 2021) of previously implemented management activities (i.e., vegetative treatments) to minimize the consequences of anticipated disturbances were not only ineffective and expensive but also reduced forest carbon storage and diminished the ability of the forest to sequester carbon.Carbon balance tradeoffs between reduced biomass density and increased forest resilience to disturbance are uncertain in large part due to the uncertainty of future natural disturbances occurring in treated areas.. . ., at the landscape level, the encounter rates between treatments and disturbance are typically low (J. L. Campbell et al 2012). Greater areas of forest must therefore be treated than will encounter a disturbance, in turn increasing any carbon cost to benefit ratio estimated at the stand scale.At a stand level, our results demonstrate that thinning strategies to reduce carbon emissions in the next decades (IPCC 2018) must either overcome inherent and persistent carbon deficits over nonmanagement or be sufficiently justified for services other than carbon storage (i.e., wood production, human hazard reduction).Harvesting (logging and thinning)Most forest management, both public and private, considers trees as the only important part of forest ecosystems and therefore treats trees as crops. That focus is not new and indicates why the U.S. Forest Service is part of the U.S. Department of Agriculture and not an agency that stands on its own, dedicated to preserving forests as an essential set of ecosystems without which human survival would be at risk.As global warming puts increasing stress on forest ecosystems, forest managers, wishing to preserve the status quo, are faced with addressing the resulting changes. The overwhelming management response is to assert that because forests no longer match historical conditions, they are more susceptible to wildfires, disease, insects, and droughts.Ignored is the fact that historical conditions (assumed but not verified) are speculative at best and that the current intensity of global warming is unknown in human history. It is not logical to spend resources on "restoring" forests to supposed historical conditions or to spend resources attempting to "improve forest resiliency," a euphemism for the protecting the status quo.Forest management's "chainsaw medicine" is based on political expediency rather than science, ill-informed, and harmful. This is especially true when such activities reduce a forest's capacity to sequester and/or store carbon, both desperately needed during this period of increasing global warming.Dry forests are particularly subject to wildfires, insect outbreaks, and droughts that likely will increase with climate change. Efforts to increase resilience of dry forests often focus on removing most small trees to reduce wildfire risk. However, small trees often survive other disturbances and could provide broader forest resilience, but small trees are thought to have been historically rare. We used direct records by land surveyors in the late-1800s along 22,206 km of survey lines in 1.7 million ha of dry forests in the western USA to test this idea. These systematic surveys (45,171 trees) of historical forests reveal that small trees dominated (52-92% of total trees) dry forests. Historical forests also included diverse tree sizes and species, which together provided resilience to several types of disturbances. Current risk to dry forests from insect outbreaks is 5.6 times the risk of higher-severity wildfires, with small trees increasing forest resilience to insect out breaks. Removal of most small trees to reduce wildfire risk may compromise the bet-hedging resilience, provided by small trees and diverse tree sizes and species, against a broad array of unpredictable future disturbances. (Baker and Williams 2015)There is a widespread view among land managers and others that the protected status of many forestlands in the western United States corresponds with higher fire severity levels due to historical restrictions on logging that contribute to greater amounts of biomass and fuel loading in less intensively managed areas, particularly after decades of fire suppression. This view has led to recent proposals[mdash]both administrative and legislative[mdash]to reduce or eliminate forest protections and increase some forms of logging based on the belief that restrictions on active management have increased fire severity. We investigated the relationship between protected status and fire severity using the Random Forests algorithm applied to 1500 fires affecting 9.5 million hectares between 1984 and 2014 in pine (Pinus ponderosa, Pinus jeffreyi) and mixed-conifer forests of western United States, accounting for key topographic and climate variables. We found forests with higher levels of protection had lower severity values even though they are generally identified as having the highest overall levels of biomass and fuel loading. Our results suggest a need to reconsider current overly simplistic assumptions about the relationship between forest protection and fire severity in fire management and policy. (Bradley 2016)Like past extreme fire events, the 2020 and 2021 fire seasons have accelerated fire policy and forest management discussions at all levels of government - federal, state, and local - including recent bills introduced in the United States Senate

(S.4625, S.4331). Many new policy discussions on fire and forest management are being based upon the misconception that harvest will protect forests from mortality and carbon loss (Executive Order, 2018; Zinke 2018; Infrastructure Investment and Jobs Act 2021; Newhouse 2021), and decrease fire risk (Forest Climate Action Team 2018) despite substantial uncertainty over long-term impacts to forest climate resilience (i.e., forest treatments may decrease forest resilience in the era of climate change). Our results and the majority of full-carbon accounting studies conclude that any type of harvest (logging or commercial thinning) decreases forest carbon storage (Law et al 2013), and this research shows harvest emits more carbon per unit area than fire at all scales. (Bartowitz 2022)According to recent research, such management actions have not accomplished what was intended and have reduced the ability of forests to store and sequester carbon.. . ., it may be better not to harvest a mature forest site because harvesting may release more CO2 than is desirable, with subsequent regeneration unable, in the short to medium term, to sequester the CO2 released. (Muller 2016) Forests pull about one-third of all human-caused carbon dioxide emissions from the atmosphere each year. Researchers have calculated that ending deforestation and allowing mature forests to keep growing could enable forests to take up twice as much carbon. (Law and Moomaw, Keeping trees in the ground where they are already growing is an effective low-tech way to slow climate change 2021) Half of a tree's stems, branches, and roots are composed of carbon. Live and dead trees, along with forest soil, hold the equivalent of 80% of all the carbon currently in Earth's atmosphere. (Law and Moomaw, Keeping trees in the ground where they are already growing is an effective low-tech way to slow climate change 2021)Mature trees that have reached full root, bark, and canopy development deal with climate variability better than young trees. Older trees also store more carbon. Old-growth trees, which usually are hundreds of years old, store enormous quantities of carbon in their wood, and accumulate more carbon annually. (Law and Moomaw, Keeping trees in the ground where they are already growing is an effective low-tech way to slow climate change 2021)Careful research into forest harvesting reveals that logging causes the majority of forest carbon emissions, many times that of natural disturbances. Forest management asserts that regrowth and tree planting will sequester the carbon that was removed. That speculation is based on assumed future conditions and ignores the fact that any carbon currently released into the atmosphere will remain in the atmosphere for many hundreds of years, continuously contributing to additional global warming. In a review that we conducted with colleagues in 2019, we found that overall, U.S. state and federal reporting underestimated wood product-related carbon dioxide emissions by 25% to 55%. We analyzed Oregon carbon emissions from wood that had been harvested over the past century and discovered that 65% of the original carbon returned to theatmosphere as CO2. Landfills retained 16%, while just 19% remained in wood products. (Law and Moomaw, Keeping trees in the ground where they are already growing is an effective low-tech way to slow climate change 2021) An important aspect of short-rotation forest management is that the carbon debt incurred on harvested sites is usually ignored, as is the fate of the wood once it is harvested. The combined carbon stored in ecosystems and products from the ecosystems is always lower when rotation intervals are shorter and harvest intensity is higher (Mitchell et al 2012). That is, harvesting with greater frequency and intensity lowers carbon storage in forests and prolongs the time needed to recoup the carbon debt. (Law and Waring, Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests 2015) Harvest is the major source of forest emissions in the US. Across the lower 48 states, direct harvest-related emissions are 7.6 times higher than all-natural disturbances (e.g., fire, insects) combined (Harris et al 2016). In the West Coast states (OR, CA, WA), harvest-related emissions average 5 times fire emissions for the three states combined (Hudiburg et al 2019). (B. E. Law, The Status of Science on Forest Carbon Management to Mitigate Climate Change 2020) While planting trees is desirable, that will contribute relatively little to carbon accumulation out of the atmosphere by 2100 compared to reducing harvest. (B. E. Law, Creating Strategic Reserves to Protect Forest Carbon and Reduce Biodiversity Losses in the United States 2022) Rather than holding ecosystems to an idealized conception of the past using historical conditions as management targets, a good understanding of the environmental co-benefits associated with large tree protection is needed to inform management strategies that contribute toward solving humanity's most pressing Earth system challenges (Millar et al 2007; Rockstr[ouml]m et al 2009; Barnosky et al 2017; Ripple et al 2020). Replacing large diameter trees with seedlings will create a major carbon loss to the atmosphere during harvest (Harris et al 2016) and not achieve storage of comparable atmospheric carbon for the indefinite future. (Mildrexler 2020) Conducting a quantitative assessment using empirical data has determined the large carbon stock that would be lost and the resulting climate consequences if these large trees are harvested. . . . Proforestation allows existing forests to continue growing without harvest or other management practices so that more trees can reach the large tree size that accumulates more carbon in the near and long term than do reforestation and afforestation (Moomaw et al 2019). No additional land is required as is the case with afforestation, and proforestation is the lowest cost opportunity . . . Intact mesic forests are ideal locations for proforestation. Harvesting large trees will add very large amounts of biogenic carbon to the atmosphere (Harris et al 2016), . . . The young trees will never be able to recover and accumulate the amount of carbon that is in the growing and older forests during these next critical decades, and will only equal current levels a century or more from now. . . . Protecting large trees to help stabilize climate is critically important for managing forest ecosystems as social-ecological systems. (Mildrexler 2020)Carbon is lost from forests in several ways: damage from natural disturbances including insects and pathogens ("pests"), fire, drought, and wind; forest conversion to development or other non-forest land; and forest harvest/management. Together, fires, drought, wind, and pests account for [sim]12% of the carbon lost in the U.S.; forest conversion accounts for [sim]3% of carbon loss; and forest harvesting accounts for 85% of the carbon lost from forests each year (Harris et al 2016). (Moomaw 2019)Our analysis indicated that logging reduces total above ground carbon stocks substantially more than wildfire . . . Further, the recovery of above ground carbon stocks appears to be much longer after logging than wildfire. (Wilson 2021) Furthermore, tree harvest disturbs the soil, reducing and releasing its carbon stores. The physical disturbance of soil, and mixing of the litter layer with surface soil during harvesting and site preparation activities results in significant redistribution of C between different pools, and triggering accelerated carbon losses (Mallik and Hu 1997). Mixing of [the] litter layer with topsoil effectively removes this structural element and exposes it to diverse microbial communities (Yanai et al 2003; Nave et al 2010; Noormets et al 2012), whereas the breaking of the physical structure of soil aggregates exposes carbon that may previously have been protected (Six et al 2002b; Diochon and Kellman 2009; Schmidt et al 2011). (Noormets 2015) Harvesting-related disturbances are the most visible, and also among the most functionally significant effects in managed forests, and on a landscape scale can account for over 90% of the variability in observed carbon exchange (Magnani et al 2007; Noormets et al 2007; Amiro et al., 2010; Dangal et al 2014). The removal of stemwood, along with the conversion of foliage and branch biomass to detritus represents a greater redistribution of pools than any natural disturbance, even fire (Harmon et al 2011). The forest floor C pool decreases by about 30 [plusmn] 6% following a harvest, with slightly greater effect in angiosperms than in gymnosperms (but see Epron et al 2006; Nave et al 2010; Nouvellon et al 2012). Even in natural forests that experience disturbances at a much lower frequency, the associated increases in heterotrophic respiration (Rh) constitute up to a half of total carbon losses over time (Harmon et al 1986, 2011). (Noormets 2015). . ., in proportion to total soil CO2 efflux (Rs), Rh increases from the typical 20-40% in mature forests to about 70-95% in young regenerating ones following the harvest (Wang et al 2002; Bond-Lamberty et al 2004b; Epron et al 2006; Noormets et al 2012). (Noormets 2015) Envisioning forest management through a lens that recognizes the importance of belowground C fluxes from living root systems (both residues and labile inputs) for belowground biodiversity and C sequestration allows us to more fully understand the ecosystem-level consequences of forestry practices. Forest harvesting, particularly clear-cut harvesting, has sudden and profound effects as inputs of labile C from living roots cease, as do turnover of fine roots and aboveground litterfall. Instead, there is an immediate pulse of detritus in the form of logging slash aboveground, followed by a pulse of dead roots and mycorrhizal hyphae belowground. This pulse sustains soil organisms in the litter-detritivoreweb as the residues decompose. However, soil organisms in the labile-microbial web are very much diminished until root systems and mycorrhizal networks are re-established. Following clear-cut harvesting, ectomycorrhizal fungal biomass, diversity, and species composition are greatly reduced (Hagerman et al 1999; Jones et al 2003; Grebenc et al 2009). Soil fungal communities shift from ectomycorrhizal to saprotrophic-dominated assemblages (Byrd et al 2000; Jones et al 2003; Busse et al 2006; Kohout et al 2018), and this shift can persist for decades after harvest (Kranabetter et al 2005; Twieg et al 2007; Spake et al 2015; Kyaschenko et al 2017). Disrupting C flow to roots through stem girdling (Yarwood et al., 2009) or root severing (Lindahl et al 2010) has similar effects, confirming that these changes are a consequence of interrupted belowground C flux to roots and mycorrhizae following clear-cut harvesting. Clear-cut harvesting also reduces microbial biomass and fungal biomass (meta-analysis by Holden and Treseder 2013) and abundances of mites, spiders, and earthworms (Abbott et al 1980; Bird and Chatarpaul 1986; Blair and Crossley 1988; Marra and Edmonds 1998).

(Prescott and Grayston 2023) Decomposition of residual SOM without replenishment of newly generated SOM following clearcut harvesting leads to a gradual reduction in SOM (soil organic matter) and SOC (soil organic carbon) stocks over 1 to 3 decades, which and may require several decades to recover (James and Harrison, 2016; Achat et al 2015). Long-term declines in SOM can occur in forests managed on a rotation basis (Harmon et al 1990; Harmon and Marks, 2002; Seely et al 2002; Dean et al 2017) if stands are harvested before SOM stocks return to pre-harvest levels. Globally, managed forests have about 50 % lower C stocks than unmanaged forests (Noormets et al 2015). . . . If belowground inputs do not keep pace with stem growth in managed forests, rotation lengths based on stem growth may lead to long-term declines in soil C. Greater depletion of the more persistent MAOM (mineral-associated organic matter) pool compared to the POM (particulate organic matter) pool (Lacroix et al 2016) and reductions in macroaggregates in clear-cut forests (Siebers and Kruse, 2019) are also probable consequences of the cessation of belowground C fluxes from living roots. Emphasis added (Prescott and Grayston 2023) Retention of living trees is also effective in retaining soil biodiversity following forest harvest, particularly if a large number or proportion of live trees are retained. In the meta-analysis of Holden and Treseder (2013), clear-cutting significantly lowered soil bacterial, fungal, and total microbial abundance, but there were no significant effects of partial harvest. . . ., in a boreal forest, fungal communities in a harvested area in which 70 % of living trees were retained were similar to those in unmanaged forests (Kim et al 2021). In a coastal Douglas-fir forest, numbers of ECM (ectomycorrhizal) fungal sporocarps were reduced by only 18 % in areas with 75 % tree retention, compared with 50 % reduction where 40 % of trees were retained, and 80 % reduction where only 15 % of trees were retained (Luoma et al 2004). . . . The abundance of ECM fungi in the O-horizon declined proportionally to the harvest intensity (Sterkenburg et al 2019). Emphasis added (Prescott and Grayston 2023)Harvesting tends to be associated with a reduction in forest floor carbon stores, with average losses in the range of [minus]20 to [minus]40% (Nave et al 2010; James and Harrison, 2016). This is in contrast to mineral soil which tends to be quite stable despite what would seem tobe a major ecosystem perturbation, like timber harvest. In rough terms, changes in mineral soil carbon storage associated with timber harvest tend to be small to moderate, with changes ranging from not significantly different to on the order of [plusmn] 15% change in mineral soil carbon (Johnson and Curtis 2001; Nave et al 2010; James and Harrison 2016). However, "no significant change" is decidedly different than verifiably zero change in soil carbon through time (Kravchenko and Robertson, 2011). A finding of "no statistical difference," when a study lacks power to detect differences in the expected range, is not a meaningful outcome. Even a small directional change could have large implications over long time periods, so investigations with higher precision a clearly still warranted. (Holub and Hatten 2019)The total forest floor mass per area is quite small compared to mineral soil masses, averaging just 46.4 Mg ha-1 pre-harvest, but it nearly doubles to 90.3 Mg ha-1 post-harvest ($p < 0.001$) due to the inputs of woody harvest residue. (Holub and Hatten 2019)Across all studies, harvesting led to a significant average decrease in soil C of 11.2% relative to control. (James and Harrison, The Effect of Harvest on Forest Soil Carbon - A Meta-Analysis 2016)Several different soil layers show significant losses of C due to harvesting. Overall, O horizons lost 30.2% of their carbon as a result of harvesting. Losses from topsoil were much smaller, although the estimated loss when reported in pool units was significant (-3.3%). In mid (15-30 cm) and deep soil (30-60 cm), the average loss of soil C was greater than topsoil, although the smaller number of response ratios for these depths resulted in more poorly constrained estimates. (James and Harrison, The Effect of Harvest on Forest Soil Carbon - A Meta-Analysis 2016)The decline in O horizon C pools is significantly greater in conifer/mixed forests ([minus]38.1%) compared to hardwood forests ([minus]25.4%). (James and Harrison, The Effect of Harvest on Forest Soil Carbon - A Meta-Analysis 2016)The practice of broadcast burning sites in preparation for planting after a harvest leads to significant additional losses of soil C, with burned soils losing 15.2% more C than soils with no pretreatment. This effect is especially severe in the O horizon (40.9% additional loss than if sites were not burned), and somewhat curtailed in the mineral soil (8.3% additional loss). The wide 95% CI for the estimate of differences in O horizon responses due to burning reflects disparities in burn severity and treatment implementation among different studies. (James and Harrison, The Effect of Harvest on Forest Soil Carbon - A Meta-Analysis 2016). . ., Achat et al (2015) showed that intensive harvests led to soil C losses in all layers of forest soils. Similarly, James and Harrison (2016) found that harvesting reduced soil C, on average, by 11.2% and there was substantial variation between responses in different soil depths, with greatest losses occurring in the O horizon. (James and others, Effects of forest harvesting and biomass removal on soil carbon and nitrogen: Two complementary meta-analysis 2021)Both the literature and LTSP meta-analyses show that whole tree harvest (WTH) with additional harvest residue (+Removal) or forest floor removal (+FF) results in significant additional soil C loss compared to bole-only (BO) harvest (-24.8 and -8.5%) in the combined soil for the literature and LTSP meta-analyses, respectively. (James and others, Effects of forest harvesting and biomass removal on soil carbon and nitrogen: Two complementary meta-analysis 2021)In the drive to harvest the greatest number of trees, forest management ignores research that exposes the damage done to soil biodiversity. (Prescott and Grayston 2023) revealed that leaving too much distance between trees not only damages soil biodiversity but diminishes the growth of newly established trees. The beneficial effect of retention patches on soil biodiversity extends a few meters into the harvested area, but becomes minimal within 10 m of the stem. This distance does not differ depending on the size of the retention patch (Hagerman et al 1999; Jones et al 2008), although the total area of the zone of influence increases with patch size. . . . Given this evidence that the influence of living trees becomes minimal within 10 m of the stem, an inter-tree spacing of no more than 15 m would be necessary to sustain belowground life throughout the harvested area.The steep decline in belowground influence of trees with distance from patch edges indicates that dispersed retention (i.e., leaving living trees uniformly dispersed across the harvested area) could be more effective at sustaining soil biodiversity in harvested forests. For the same level of retention, Luoma et al (2004) found smaller reductions in fall mushroom and truffle biomass in dispersed compared to aggregated retention blocks.Retaining patches of mature living trees during harvest (i.e. aggregated retention) sustains soil biodiversity within the patch and for a few meters into the opening around each patch. The influence of living roots declines with distance from the stem and is generally negligible by 10 m from the stem. Therefore, to sustain life below ground, living trees also need to be dispersed throughout the cutblock, with inter-tree distances no greater than about 15 m. This requires a minimum of 40 retention trees per hectare dispersed throughout the cutblock.Equating tree influence with tree height assumes that the major effects of a tree are casting shade and wind. While forest influence on wind and light can be detected 25 to 50 m (one to two tree lengths) into the harvested area, forest influence on other values such as plant species, soil nutrients and soil organisms extend less than 10 m from the forest edge (Mitchell et al 2004). Replacing 'tree height' with either '10 m from stem', or 'distance from stem to drip line', as the estimate of tree influence would make retention forestry more conducive to sustaining the belowground ecosystem.Forest managers assert that fuel treatments (logging and thinning) are necessary to save the remaining trees from wildfires. However, forest carbon stores and the ability of the treated area to sequester carbon are immediately reduced by fuel treatments. Plus, most of the carbon stored in trees removed by logging and thinning is immediately transformed into atmospheric CO2. Given global warming and the need to increase carbon storage and sequestration, suchtreatments are illogical. The lack of logic behind fuel treatments was revealed more than a decade ago by (Campbell 2011).. . ., fuel treatments were effective in reducing combustion in a subsequent wildfire, and the greater the treatment intensity, the greater the reduction in future combustion. However, even in the mature, fire-suppressed ponderosa pine (Pinus ponderosa) forest, protecting one unit of C from wildfire combustion typically came at the cost of removing three units of C in treatment. The reason for this is simple: the efficacy of fuel-reduction treatments in reducing future wildfire emissions comes in large part by removing or combusting surface fuels ahead of time. Furthermore, because removing fine canopy fuels (i.e., leaves and twigs) practically necessitates removing the branches and boles to which they are attached, conventional fuel-reduction treatments usually remove more C from a forest stand than would a wildfire burning in an untreated stand.Any approach to C accounting that assumes a wildfire burn probability of 100% during the effective life span of a fuel-reduction treatment is almost certain to overestimate the ability of such treatments to reduce pyrogenic emissions on the future landscape. Inevitably, some fraction of the land area from which biomass is thinned will not be exposed to any fire during the treatment's effective life span and therefore will incur no benefits of reduced combustion (Rhodes and Baker 2008).Among fire-prone forests of the western US, the combination of wildfire starts and suppression efforts result in current burn probabilities of less than 1%. Given a fuel-treatment life expectancy of 10-25 years, only 1-20% of treated areas will ever have the opportunity to affect fire behavior. Such approximations are consistent with a similar analysis reported by Rhodes and Baker (2008), who suggested that only 3% of the area treated for fuels is likely to be exposed to fire during their assumed effective life span of 20 years. Extending treatment efficacy by repeated burning of understory fuels could considerably increase the likelihood of a treated stand to affect wildfire behavior, but such efforts come at the cost of more frequent C loss.A full accounting of C would also include the fossil-fuel costs of conducting fuel treatments, the longevity of forest products removed in fuel treatments, and the ability of fuel treatments to produce renewable "bioenergy", potentially offsetting combustion of fossil fuels.While performing a study of harvest intensity, (Simard 2020) found how biodiversity and carbon stocks were negatively affected, both above- and below-ground.To quantify the effect of harvest intensity on C stocks and biodiversity, we compared five harvesting intensities (clearcutting, seedtree retention, 30% patch retention, 60% patch retention, and uncut controls) across a climatic aridity gradient that ranged from humid to semi-arid in the Douglas-fir (Pseudotsuga menziesii) forests of British Columbia. We found that increased harvesting intensity reduced total ecosystem, aboveground, and live tree C stocks 1 year postharvest, and the magnitude of these losses were negatively correlated with climatic aridity. In humid forests, total ecosystem C ranged from 50% loss following clearcut harvest, to 30% loss following large patch retention harvest. In arid forests thisrange was 60 to 8% loss, respectively. . . . Belowground C stocks declined by an average of 29% after harvesting, with almost all of the loss from the forest floor and none from the mineral soil. Of the secondary pools, standing and coarse deadwood declined in all harvesting treatments regardless of cutting intensity or aridity, while C stocks in fine fuels and stumps increased. . . . This study showed that the highest retention level was best at reducing losses in C stocks and biodiversity, and clearcutting the poorest, and while partial retention of canopy trees can reduce losses in these ecosystem services, outcomes will vary with climatic aridity.Our study revealed significant losses in total ecosystem C stocks and biodiversity with increasing harvesting intensity, and the magnitude of losses was greater in more humid, productive ecosystems than semi-arid interior Douglas-fir forests. The greatest losses occurred with clearcutting, generally followed by the seedtree, small patch, then large patch retention treatments, with nuanced differences observed between the intermediate retention treatments among climatic regions.Any level of harvesting reduced ecosystem C stocks and biodiversity across the entire aridity gradient. Overall, the magnitude of ecosystem C and tree species diversity losses were greatest in the most humid, productive forests, whereas loss of understory bryoid species was greatest in the arid forests, with all of these losses increasing with harvest intensity. Clearcuts performed the worst at conserving ecosystem services and the large patch retention treatments the best, with intermediate responses in the low retention treatments (seedtree and small patch retention). Where moderate levels of harvesting are sought, retention of small intact patches was better at conserving C stocks and biodiversity in arid regions, whereas the seed tree strategy generally performed as well as small patches in the more humid forests. These results suggest that as climate changes and aridity increases, clearcutting is not the treatment of choice if protection of ecosystem C stocks and biodiversity is a high priority. One of the important overall findings of this analysis was that C stocks in forest floors were highly vulnerable to loss with any level of harvesting (-61% on average) compared with mineral soils (no significant change), and the organic matter losses were greater than in studies elsewhere.Research by (Stenzel 2021) found that thinning to increase residual tree resistance to stressors may reduce the probability of mortality, but also decreases ecosystem carbon storage. The study also found that the C emissions possibly avoided can be far less than the emission associated with harvest. Additional results indicated that the decrease in tree density was not compensated by an increase in residual tree growth. Overall, this research questions the feasibility of forest thinning.To justify specific removal treatments for carbon storage benefits, the net emissions costs of thinning must be lower than the costs of inaction at the temporal and spatial scales of focus, regardless of an ecosystem's baseline sink or source strength (Hudiburg et al 2011; Law et al 2013; Mitchell et al 2012; Naudts et al 2016).Thinning for disturbance mitigation is intended to generally increase residual tree resistance to stressors, increasing individual tree carbon and water status and decreasing probability of mortality. However, killing live tree biomass can decrease ecosystem carbon storageover baseline conditions on decadal scales (Goetz et al 2012), with storage losses, time until recovery, and residual tree growth positively correlated with thinning intensity (Zhou et al 2013).Forest thinning emissions result primarily from the harvest and eventual decomposition or combustion of killed above and belowground biomass. Because harvests differ from natural disturbances in that large quantities of stem biomass are often removed and are emitted off site, conducting a LCA (life cycle assessment) of biomass fates is critical to estimating carbon emissions, as no biomass is stored indefinitely (Goetz et al 2012; Hudiburg et al 2011, 2019). Avoided emissions (e.g., combustion during a subsequent or avoided fire) should also be accounted for, but because fire is stochastic, and will occur in only a fraction of a treated landscape during treatment lifespans, these avoided emissions are difficult to quantify (J. L.

Campbell & Ager 2013). Moreover, the emissions avoided can be less than emissions associated with harvest, depending on the harvest intensity (Berner et al 2017).Treatment response magnitude and direction was variable; 20% of thinned stand trees did not display increases in radial growth, 50% displayed increases of less than 25%, and 15% of trees displayed increases of over 100%,At the stand scale, decreases in tree density were not compensated by the increases in tree growth, and NPP (net primary production) decreased by 45% in thinned stands, ([minus]245 [plusmn] 23 g C m[minus]1 yr[minus]1, $p < 0.05$, paired T-test). During the same period, control plot NPP declined by 3% ([minus]25 [plusmn] 11 g C m[minus]1 yr[minus]1).Thinning resulted in an average 48 and 10 Mg C ha[minus]1 of killed above and belowground biomass, with 37.4 Mg C ha[minus]1 removed from site. [sim]35% of killed biomass remained on site, 18% was combusted as slash or left as debris, and 65% was removed.A multidecadal ecosystem biomass (i.e., carbon) deficit following moderate and heavy partial harvest is supported by most analyses of mid- to long-term thinning structural impacts (James et al 2018; Zhou et al 2013), . . .InsectsForest managers operate on the theory that thinning and logging will reduce tree mortality if the treated area is attacked by mountain pine beetles (MPB). Research by (Morris 2023) found that, although pre MPB outbreak logging and thinning are unlikely to affect fire likelihood, those treatments shift fuel loads[mdash]more canopy fuel, less surface fuel[mdash]and will influence fire behavior. The research also found that logged and thinned areas which later experienced MPB attacks not only suffered the initial removal of live biomass but were likely to experience an additional reduction of long-term carbon stability.Although beetle outbreaks may not affect fire likelihood (Meigs and others 2015) or area burned (Hart and others 2015), beetle-induced tree mortality and shifts in fuel profiles can influence fire behavior (that is, fire reaction to influences of fuel, weather, and topography; NWCG 2021) by altering surface and crown fire likelihood through redistribution of live anddead fuels over time (Simard and others 2011; Collins and others 2012; Woolley and others 2019) and changing microclimate conditions (Page and Jenkins 2007).Beyond the initial removal of live biomass, historically cut stands are also likely to be susceptible to future beetle outbreaks sooner than uncut stands due to greater live basal area and density (Collins and others 2011), suggesting historical silvicultural treatments may reduce long-term C stability.Taking a long-term view, recent warming conditions seem to have contributed to beetle outbreaks[mdash]winters are too warm to reduce overwintering beetle populations[mdash]beetles perform what may be a helpful forest evolution by transferring carbon from live to dead pools where it is slowly released to the atmosphere[mdash]well within Earth's buffering capacity[mdash]and becomes available for consumption by other living organisms.There is no question that MPB kill trees, but often ignored is the fact that dead and dying trees make possible an increase of resources for other plants. Another overlooked benefit to beetle infestation is the possible conversion to different ecosystem balances and other forest types.Research by (Ghimire 2015) revealed that the amount of tree biomass killed by beetles is uncertain because of insufficient surveys into the extent and severity of beetle killed forests.Warmer conditions over the past two decades have contributed to rapid expansion of bark beetle outbreaks killing millions of trees over a large fraction of western United States (US) forests. These outbreaks reduce plant productivity by killing trees and transfer carbon from live to dead pools where carbon is slowly emitted to the atmosphere via heterotrophic respiration which subsequently feeds back to climate change.We find that biomass killed by bark beetle attacks across beetle-affected areas in western US forests from 2000 to 2009 ranges from 5 to 15 Tg C yr -1 and caused a reduction of net ecosystem productivity (NEP) of about 6.1-9.3 Tg C y -1 by 2009. Uncertainties result largely from a lack of detailed surveys of the extent and severity of outbreaks, calling out a need for improved characterization across western US forests.Bark beetle infestations have both physical and biological effects leading to substantial changes to forest ecosystems (Samman & Logan, 2000). Bark beetle outbreaks cause tree mortality leading to changes in forest structure and composition (Bigler et al 2005; Jenkins et al 2008). Beetle-killed forests are characterized by a higher proportion of standing dead trees (snags) and have more coarse woody debris and fine litter than before disturbance (Jenkins e 2008; Klutsch et al 2009; Jorgensen & Jenkins, 2011). This can lead to elevated resource availability for surviving trees due to increased light, nutrients, and moisture at the forest floor (Stone & Wolfe, 1996). Modifications in the biotic and abiotic environment can alter future disturbance regimes and lead to transformations in size, distribution, and composition of forests (Collins et al 2011; Simard et al 2011). These structural and compositional changes impact forest function including water (Helie et al., 2005), energy (Amiro et al., 2006), and carbon (Kurz et al 2008; Edburg et al 2011; Stinson et al 2011) balances.The primary mechanism of bark beetle impacts to ecosystem carbon balance is through foliage loss and tree mortality, and the associated reduction in productivity (Hicke et al 2012). However, a few years after the insect infestation, forests regenerate and can attain or exceed pre-disturbance productivity levels depending on nutrient status, seed, and sapling availability, climatic conditions, and competition.. . ., it is possible that severe beetle damage would lead to a change in forest type or conversion (Collins et al 2011).WildfireWildfire is the most discussed forest disturbance by far, no doubt because humans have an innate fear of fire, it appears to be haphazard, and, in many cases, the resulting changes are abrupt[mdash]humans do not like abrupt change.Currently, wildfire provides the largest and most reliable income stream for the U.S. Forest Service (USFS) and the Bureau of Land Management (BLM)[mdash]more than 50% of the USFS's funding derives from vegetative treatment to reduce wildfire and fighting the inevitable fires. So, when those agencies make assertions about the reasons for forest treatments to change wildfire behavior, their claims must be examined with that income stream in mind.Rather than directly addressing the underlying cause of increasing wildfire activity, fossil fuel emissions (FFE), the USFS and BLM follow the money and concentrate on forest treatments[mdash]that's where the money is!Fire catastrophes will continue to occur and worsen if we do not focus on decreasing FFE, the primary driver of climate change (IPCC, 2018). (Bartowitz 2022)Results by (Coulston 2023) strongly suggested that current wildfire reduction strategies, vegetation treatments, reduce short-term carbon sequestration benefits. Because those treatments immediately increase the amount of carbon transferring to the atmosphere and the effect will last hundreds of years, such management actions increase global warming.Our results suggest that wildfire reduction strategies reduce carbon sequestration potential in the near term but provide a longer-term benefit. Planting initiatives increase carbon sequestration but at levels that do not offset lost sequestration from wildfire reduction strategies.Results for the fuel-treatment scenarios suggest a negative mitigation potential in the near-term largely due to the removal of live trees. In the longer term, projections suggest a positive, but small, mitigation potential largely due to increased growth of thinned stands and reduced fire mortality.Government agencies allow, even encourage, elected officials, the media, and the public to mistakenly believe that when a wildfire occurs in a forest, huge amounts of carbon are released to the atmosphere. However, independent researchers determined that relatively small amounts of forest carbon are released to the atmosphere by wildfire. Litter and duff on the forest floor, along with small trees and understory shrubs, are the most combustible material ina forest. The main bole and most branches of a life tree are not consumed and, standing and downed dead trees are minimally incinerated. Knowing that the agencies' main income streams depend on the belief that only they can protect forests from wildfire, it is no wonder that agencies not only allow but encourage the belief that wildfires instantly release huge amounts of carbon into the atmosphere. There are many fallacies about forest carbon storage, such as the concern that wildfires in the American West are releasing huge quantities of carbon into the atmosphere. In fact, fires are a relatively small carbon source. For example, the massive Biscuit Fire, which burned 772 square miles in southwest Oregon in 2002, emitted less than 10% of Oregon's total emissions that year. (Law and Moomaw, Keeping trees in the ground where they are already growing is an effective low-tech way to slow climate change 2021) Recent Pacific Northwest wildfires have emitted less carbon to the atmosphere than previously thought. This is mostly due to previous overestimates of combustion losses by fire (Campbell et al 2007), and uncertainty in remotely sensed estimates of burnt areas in different severity classes (Meigs et al 2009). In mixed conifer forests of western North America, nearly all contemporary fires are mixed-severity. (Law and Waring, Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests 2015)In a comparison of pre-and post-fire carbon pools on a 200,000 ha mixed severity fire, only 1-3% of stem carbon was combusted in trees larger than [sim]8 cm diameter, and the percentage only increases up to 12% on large standing dead stems (Campbell et al 2007). . . . In this study, low- and moderate-severity fire released 58% and 82% as much carbon emissions, respectively, as high severity fire. In all five fires small trees, understory shrubs, litter and duff represented the majority of material combusted. In general, dry forest floor litter is more likely to burn than large stems with moist sapwood. (Law and Waring, Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests 2015) . . ., harvest-related emissions from thinning are much higher than potential reduction in fire emissions. In west coast states, overall harvest-related emissions were about 5 times fire emissions, . . . In the conterminous 48 states, harvest-related emissions are 7.5 times those from all natural causes (Harris et al 2016). It is understandable that the public wants action to reduce wildfire threats, but false solutions that make the problem worse and increase global warming are counterproductive. (B. E. Law, Creating Strategic Reserves to Protect

Forest Carbon and Reduce Biodiversity Losses in the United States 2022)As wildfire generally only consumes finer material such as leaf litter, foliage and smaller stems and logs, relatively little forest carbon is released by the fire itself (Keith et al 2014a, Keith et al 2014b). (Wilson 2021)The biomass killed but not consumed during forest fires releases carbon to the atmosphere but slowly enough to remain well within Earth's buffering capacity. It appears that vegetative treatments to reduce crown fire exceed any hopeful gain.The biomass killed in fires eventually decomposes, slowly releasing carbon to the atmosphere over decades to centuries (Law and Harmon, 2011; Campbell et al 2011). About half of the carbon remaining on site after a fire, stays in soil for about 90 years, and the other half persists for more than 1,000 years as charcoal (Singh et al 2012). (Law and Waring, Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests 2015) The amount of carbon lost from the treatments intended to reduce crown fire risk exceeded the gain from reducing burn probability and fire severity, even over long periods. (Law and Waring, Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests 2015) While moderate to high severity fire can kill trees, most of the carbon remains in the forest as dead wood that will take decades to centuries to decompose. Less than 10% of ecosystem carbon enters the atmosphere as carbon dioxide in PNW forest fires (Law and Waring 2015; Mitchell et al 2009). Recent field studies of combustion rates in California's large megafires show that carbon emissions were very low at the landscape-level (0.6 to 1.8%) because larger trees with low combustion rates were the majority of biomass, and high severity fire patches were less than half of the burn area (Stenzel et al 2019; Harmon et al 2022). These findings are consistent with field studies on Oregon's East Cascades wildfires and the large Biscuit Fire in southern Oregon (Meigs et al 2009; Campbell et al 2007). (B. E. Law, Creating Strategic Reserves to Protect Forest Carbon and Reduce Biodiversity Losses in the United States 2022) We predict that logging will reduce in situ forest carbon stocks more than wildfire and take longer to recover. (Wilson 2021). . ., because most pyrogenic emissions arise from the combustion of surface fuels, and most of the area within a typical wildfire experiences surface-fuel combustion, efforts to minimize overstory fire mortality and subsequent necro-mass decay are limited in their ability to reduce fire-wide pyrogenic emissions. (Campbell 2011)A review of fuel-reduction treatments carried out in semiarid conifer forests in the western US reveals that aboveground C losses associated with treatment averaged approximately 10%, 30%, and 50% for prescribed fire only, thinning only, and thinning followed by prescribed fire, respectively. By comparison, wildfires burning over comparable fire-suppressed forests consume an average 12-22% of the aboveground C (total fire-wide averages reported by Campbell et al [2007] and Meigs et al [2009], respectively). (Campbell 2011) In the case of forest fire, direct emissions result from combustion of biomass stocks, but typically account for less than 30% of aboveground carbon, are small in relation to subsequent decomposition after high-severity fire, and are primarily limited to dead biomass on the forest floor (J. Campbell et al 2007; J. L. Campbell et al 2016; Harris et al 2019; Meigs et al 2009; Stenzel et al 2019). (Stenzel 2021)Included with the claims of total forest destruction and massive amounts of carbon released by wildfire are exaggerations about the effectiveness of vegetative treatments. Current researchreveals that, rather than consuming resources attempting to change the current environment of forests to protect human infrastructure from wildfire, making homes more fire resistant is far more effective at protecting infrastructure from damage. As to the effectiveness and likelihood that thinning might have an impact on fire behavior, the area thinned at broad scales to reduce fuels has been found to have little relationship to area burned, which is mostly driven by wind, drought, and warming. A multi-year study of forest treatments such as thinning and prescribed fire across the western U.S. showed that about 1% of U.S. Forest Service treatments experience wildfire each year (Schoennagel et al 2018). The potential effectiveness of treatments lasts only 10-20 years, diminishing annually (Schoennagel et al 2018). Thus, the preemptive actions to reduce fire risk or severity across regions have been largely ineffective. (B. E. Law, Creating Strategic Reserves to Protect Forest Carbon and Reduce Biodiversity Losses in the United States 2022) Our findings support the hypothesis that logging history would have a stronger effect on total above ground carbon stocks than wildfire history. Our models predict logging to cause a 60.6% and 85.9% decline in median above ground carbon stocks. . . . By contrast, wildfire caused a 7.3% and 46.7% decline in median above ground carbon stocks . . . (Wilson 2021) . . ., once crown fire is initiated, greater abundance and spatial homogeneity of live canopy cover (that is, greater fuel continuity) in historically cut stands may increase potential for transition from passive to active crown fire compared to uncut stands (Jenkins and others 2008). Further, greater CBD (canopy bulk density) in historically cut stands may facilitate greater canopy fuel consumption and faster crown fire spread than uncut stands (Van Wagner 1977; Linn and others 2013; although see Moriarty and others 2019), though increased horizontal heterogeneity in ACFL (available canopy fuel load) in cut stands (that is, reduced fuel continuity) may dampen this effect (Pimont and others 2006; Donato and others 2013a). Emphasis added (Morris 2023) There is a widely held perception that the severity and size of recent fires are directly related to the fuels that have accumulated in the understory due to a lack of forest management to reduce these fuels (i.e., pulping, masticating, thinning, raking, and prescribed burning; Reinhardt et al 2008; Bradley et al 2016). However, some evidence suggests that proforestation should actually reduce fire risk and there are at least three important factors to consider: first, fire is an integral part of forest dynamics in the Western U.S.; second, wildfire occurrence, size, and area burned are generally not preventable even with fuel removal treatments (Reinhardt et al 2008); and third, the area burned is actually far less today than in the first half of the twentieth century when timber harvesting was more intensive and fires were not actively suppressed (Williams, 1989; National Interagency Fire Center, 2019). Interestingly, in the past 30 years, intact forests in the Western U.S. burned at significantly lower intensities than did managed forests (Thompson et al 2007; Bradley et al 2016). Increased potential fuel in intact forests appear to be offset by drier conditions, increased windspeeds, smaller trees, and residual and more combustible fuels inherent in managed areas (Reinhardt et al 2008; Bradley et al 2016). Rather than fighting wildfires wherever they occur, the most effective strategy is limiting development in fire-prone areas, creating, and defending zones around existing development (the wildland-urban interface), and establishing codes for fire-resistant construction (Cohen, 1999; Reinhardt et al 2008). (Moomaw 2019) Older forests experience lower fire-severity compared with younger, intensively managed forests, even during extreme weather conditions (Zald and Dunn, 2018). A shift in policy and management from restoring ecosystems based on historical baselines to adapting to changing fire regimes and from unsustainable defense of the wildland-urban interface to developing fire-adapted communities is needed (Schoennagel et al 2017). (Mildrexler 2020) Research shows that wildfire occurs on only 1% of forest after treatment. And, previous logging and thinning influences how wildfire acts when it does occur. In gray stage stands, decreases in fire severity have been observed for some surface and crown fire metrics (for example, tree mortality, char height) under moderate burning conditions (that is, relatively low temperature and winds, high humidity; though see Agne and others 2016) due to less abundance of available fine fuels and live vegetation susceptible to wildfire (Harvey and others 2014a; Meigs and others 2016). . . ., under moderate burning conditions, our findings suggest historically cut stands may experience increased fire severity compared to uncut gray stage stands due to greater live foliage and 1-hr canopy fuels. However, extreme burning conditions would likely overwhelm these fuel effects, reducing or eliminating differences in fire severity among cut and uncut gray stage stands, (Morris 2023) While years since harvest was strongly associated with forest ALC (aboveground live carbon) density in young managed forests, years since fire was only weakly associated with ALC density in old unmanaged forests, and the number of fires on a given site over time was not a significant predictor of forest ALC density. Fires differ strongly from harvesting in their impact on vegetation and ALC dynamics, and fires are much more heterogeneous in their impact compared to management (Franklin et al 2002). Emphasis added (Zald 2016) Drought Earth is experiencing global warming which triggers extreme weather. Although extended periods of drought have happened before, a warmer Earth causes an increase in extreme weather events, one of which is prolonged periods of drought. Forests that experience protracted droughts undergo ecosystem shifts that include changes to plant and animal species. Certain individuals of a tree species survive, others do not as the effects of water shortages accrue. Research reveals that it is the older trees[mdash]the ones typically removed during logging projects[mdash]that are most able to withstand extended drought. Forest managers should assume that droughts will stress forests and prepare accordingly by refraining from implementing projects that include the removal of old trees which, coincidentally, are also one of the largest carbon stores in a forest.. . ., we show that tree mortality concomitant with drought has led to short-term (mean 5 y, range 1 to 23 y after mortality) vegetation-type conversion in multiple biomes across the world (131 sites). Self-replacement of the dominant tree species was only prevalent in 21% of the examined cases and forests and woodlands shifted to nonwoody vegetation in 10% of them. . . . Drought characteristics, species-specific environmental preferences, plant traits, and ecosystem legacies govern post-drought species turnover and subsequent ecological trajectories, with potential far-reaching implications for forest biodiversity and ecosystem services. (Batllori 2020)Physiological sensitivity to climate also varies with tree size. The relative sensitivity of leaf stomata to high evaporative demand is greater in young than old ponderosa pine (Irvine et al 2004), and young trees are more susceptible to soil water deficits due to shallower rooting and their greater vulnerability of their roots to broken water columns (Domec et al 2004). Over the course of dry summers, [sim]20%, 45% and 47% of water used by young, mature and old pine trees in sandy soils is extracted from below 80 cm depth (Irvine et al 2004). Hydraulic redistribution from deep soil layers will be missed, along with the added storage capacity, if models that assume 1 m soil depth. (Law and Waring, Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests 2015)The effects of water deficits accumulate, increasing injury to a tree's water conducting system dependent on the duration and severity of drought (Miao et al 2009; Mueller et al 2005). During the extreme drought years of 2001 and 2002, old ponderosa pine trees in Oregon showed only a small decline in water transport efficiency to leaves (11-24%) whereas in mature pine, the efficiency declined by 46%, and for young pine, by 80% (Irvine et al 2004). The ability of young pine to open their stomata more widely than older trees, increases the rate that water flows through a unit of their sapwood. As a result, younger trees risk the breakage of a larger proportion of their water columns, which may account for the high mortality in a young ponderosa pine plantation in California (Goldstein et al 2000). (Law and Waring, Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests 2015). . ., increasing drought and excessively large, disturbed areas could hamper post-disturbance tree regeneration (Hansen et al 2018; Harvey et al 2016), and thus lead to increased C losses after disturbance. (Dobor 2018) Extractions Forest management has focused on extracting economic value (i.e., timber) since before the birth of the United States. For much of that period, the production of sawlogs provided most of the immediate financial benefit.Sawlog production has not ended. However, now timber products are being pushed as a substitute for building products that are more fossil fuel intensive. Recently, while attempting to maximize profitability, forest managers have also begun incorporating the production of biofuels, claiming they can reduce greenhouse gas emissions by substituting for fossil fuels. Here, we look at whether studies and research support those declarations. Forest Products There are many claims that the use of wood harvested from forests should be substituted for other building materials (steel and concrete) higher carbon footprints. Articles written about this subject usually fall short by omitting portions of the life cycle of wood products and overestimate the willingness of the building industry to adjust to different materials.A complete life cycle assessment (LCA) includes the land-based carbon (net biome production, accounting for fire emissions and decomposition after disturbance), and tracks carbon losses during transport, manufacturing, combustion, and fossil fuel substitution benefits. Two misunderstandings have occurred in conducting life cycle assessments. First, such assessments cannot ignore carbon stocks present on the land, as these stocks influence the concentrations of CO_2 in the atmosphere and are clearly affected by land management (Schulze et al 2012; Law and Harmon 2011). Second, benefits attributed to product substitution are commonly overestimated. Substituting wood for aluminum and steel can displace fossil fuel emissions, but the displacement period needs to be part of the accounting. Displacement occurs until the building is replaced, and then the substitution can be renewed by a new building or it can be lost by using a material with a higher energy cost. In addition, it is often assumed that product substitution will reduce the demand for fossil fuel. However, due to human behavior and current economic systems that ignore adverse externalities, reducing resource consumption through substitution or improvements in efficiency rarely reduce fossil fuel use (York 2012). Therefore, benefits may be substantially lower and the payback period much longer and smaller for the carbon debt from intensified management and avoided fossil fuel combustion than commonly assumed (Haberl et al 2013). (Law and Waring, Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests 2015). . ., recent science indicates that forests hold carbon much longer intact than when products from them are harvested and utilized. Harvested wood product can be stored at most on average 80-150 years in structural wood for housing or in landfills where it decomposes slowly, or short-term (e.g., paper), which decomposes rapidly. Pacific Northwest harvests generate merchantable wood that is about 50-60% of the total wood harvested and an average of 54% of the wood product remains in use or end up in landfills after 20 years where it decomposes (Smith et al 2006). The remainder returns to the atmosphere within about 90-150 years and there are losses over time, not just at the end of product use. These loss rates are much higher than those from forests through the normal decomposition process and frequent harvesting increases these rates still further.(Law and Waring, Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests 2015). . . In the Western US states, the significant carbon losses from the forest are primarily from removals of wood through harvest, decomposition or burning of aboveground and belowground harvest residues, and wildfire (Law and Waring 2015). Significant harvest has been occurring in the western US since the early 20th century (figure S2). Up to 40% of the harvested wood does not become a product and the products themselves decay over time, resulting in product accumulation much smaller than the total amount harvested (figure 2(a); solid line) (Harmon et al 1996, Dymond 2012, Williams et al 2016, EPA 2017). (Hudiburg 2019)It is argued that there may be reductions in fossil carbon emissions when wood is substituted for more fossil fuel intensive building materials (e.g. steel or concrete) or used as an alternative energy source (Butarbutar et al 2016). Substitution is a one-time credit in the year of the input. Studies have reported a range of substitution displacement factors (from negative to positive displacement; Sathre and O'Connor 2010, Smyth et al 2017), but we found no study that has tracked the actual amount of construction product substitution that is occurring or has occurred in the past in the United States. This makes substitution one of the most uncertain parts of this carbon budget. (Hudiburg 2019)Substitution of wood for more fossil carbon intensive building materials has been projected to result in major climate mitigation benefits often exceeding those of the forests themselves. A reexamination of the fundamental assumptions underlying these projections indicates long-term mitigation benefits related to product substitution may have been overestimated 2- to 100-fold. (Harmon 2019, Harmon 2019)While wood-based building materials generally embody less fossil-derived energy in their manufacture than steel and concrete, resulting in a net displacement of fossil carbon, its effectiveness as a climate mitigation strategy depends on the amount of carbon displaced and its duration. Current estimates of climate mitigation benefits of product substitution are generally based on three critical, often unstated assumptions: (1) the carbon displacement value remains constant (B[ouml]rjesson P and Gustavsson L 2000; Glover et al 2002; Lippke et al 2011; Perez-Garcia et al 2005; Schlamadinger and Marland 1996; Hennigar et al 2008; Upton et al 2008; Eriksson et al 2007; Gustavsson et al 2006), (2) the displacement is permanent and therefore of infinite duration (Schlamadinger and Marland 1996; Hennigar et al 2008; Upton et al 2008; Eriksson et al 2007; Gustavsson et al 2006) which implies no losses via cross-sector leakage, and (3) there is no relationship between building longevity and substitution longevity(Lippke et al 2011; Perez-Garcia et al 2005; Schlamadinger and Marland 1996; Hennigar et al 2008; Upton et al 2008). (Harmon 2019)Although most analyses of product substitution benefits implicitly assume a constant displacement value over time constant (B[ouml]rjesson P and Gustavsson L 2000; Glover et al 2002; Lippke et al 2011; Perez-Garcia et al 2005; Schlamadinger and Marland 1996; Hennigar et al 2008; Upton et al 2008; Eriksson et al 2007; Gustavsson et al 2006), it is subject to change. Schlamadinger and Marland (1996) hypothesized energy substitution displacement values increase over time because of increased efficiencies. For productsubstitution, I hypothesize it will likely move in the opposite direction for three reasons. First, changing manufacturing methods impact embodied energy: for example, as long as it is available, the addition of fly ash could lead to a 22%-38% reduction in embodied energy required for concrete reducing the displacement value (Hammond and Joes 2008). At the same time, increased processing of wood to create materials suitable for taller buildings (e.g. cross laminated timbers) would likely lead to a lower displacement value given laminated beams have 63%-83% more embodied energy than sawn softwoods (Glover et al 2002; Hammond and Joes 2008). Second, the increases in energy efficiency hypothesized by (Schlamadinger and Marland 1996) related to rising energy costs and recycling (Glover et al 2002; Saghafi and Teshnizi 2011; Tormark 2002) and as noted by (B[ouml]rjesson P and Gustavsson L 2000; Gustavsson et al 2006) would also result in a decrease in product substitution displacement because the key relationship involves the difference in emissions and not the ratio as in energy substitution (Sathre and O'Connor 2010) (see supplemental information is available online at stacks.iop.org/ERL/14/065008/mmedia for detailed analysis of the displacement formula). Finally, changing the mix of fossil fuels used to generate energy can also substantially change the amount of carbon released per unit energy consumed and if natural gas continues to increase relative to coal, as has been observed (Hayhoe et al 2002), then the displacement value would likely decline in the future. The same is true if non-fossil energy sources such as solar, wind, or hydropower are increasingly used as projected (US Energy Information Agency 2017). (Harmon 2019)The key assumption of no relationship between product longevity and product substitution longevity has been asserted (Lippke et al 2011), but not fully explained. (Harmon 2019)Studies of substituting wood products for other building materials are often based on assumptions which are untested or unsupported.. . ., we conclude suggesting that many studies assessing forest management or products for climate change mitigation depend on a suite of assumptions that the literature either does not support or only partially supports.

(Howard 2021)It is important to carefully analyze the science informing policy focused on forest carbon strategies for climate change mitigation. In particular, there is interest in the role that forest biomass can play in substituting fossil fuels and non-biomass materials, a great deal of which is associated with the role of long-lived wood products in the construction sector (Pingoud et al 2011; Chen et al 2018; Law et al 2018; Hennigar et al 2008; Miner et al 2010; Hudiburg et al 2019; Law and Harmon 2011; Naudts et al 2016). However, analyses of those mitigation strategies depend on assumptions about production levels, economic pricing, markets, and technologies that remain largely untested. (Howard 2021). . ., there is an ongoing debate on the real or potential substitution role of HWP (harvested wood products), yet many studies assessing forest management or products for their climate change mitigation potential depend on a suite of assumptions that the literature either does not support or only partially supports (Howard et al 2021). Recent analyses suggest the actual mitigation benefits of HWP substitution may be overestimated by 2-100 times due to these assumptions (Harmon 2019; Howard et al 2021). Emphasis added (Bysouth 2024)Since perceived HWP substitution benefits are often incorporated into forestry sector GHG accounting and life cycle analyses, overestimated substitution effects could lead to policies misaligned with GHG mitigation goals. An improved understanding of HWP substitution dynamics is needed to ensure mitigation policies based on forestry sector GHG accounting reflect the most appropriate, scientifically supported strategies. (Bysouth 2024). . . , arguments that forests better serve emissions reduction targets when logged and put into harvested wood products or burned as biomass depend on several assumptions, including that the forestry sector has nearly zero or negative emissions (Malcolm et al 2020; Peng et al 2023). In contrast, our analyses show that, in Canada, forestry activities are a relatively large source of GHG emissions (roughly equivalent to emissions from the energy sector). (Bysouth 2024)Worldwide, the amount of carbon stored in harvested wood products (HWP) on an annual basis is miniscule. If socioeconomic conditions deteriorate, as they will increasingly do as Earth warms, harvested wood products can turn into another carbon source.We estimated the carbon stored within HWPs from 1961 to 2065 for 180 countries following IPCC carbon-accounting guidelines, consistent with Food and Agriculture Organization of the United Nations (FAOSTAT) historical data and plausible futures outlined by the shared socioeconomic pathways. We found that the global HWP pool was a net annual sink of 335 Mt of CO2 equivalent (CO2e)[middot]y[minus]1 in 2015, offsetting substantial amounts of industrial processes within some countries, and as much as 441 Mt of CO2e[middot]y[minus]1 by 2030 under certain socioeconomic developments. . . . However, even under favorable socioeconomic conditions, and when accounting for the sequestration gap, carbon stored annually in HWPs is <1% of global emissions. Furthermore, economic shocks can turn the HWP pool into a carbon source either long-term[mdash]e.g., the collapse of the USSR[mdash]or short-term[mdash]e.g., the US economic recession of 2008/09. In conclusion, carbon stored within end-use HWPs varies widely across countries and depends on evolving market forces. (Johnston and Radeloff 2019). . ., few have projected future carbon emissions and removals in the HWP pool, and those that have focused on regional- or national-level estimates and employed ad hoc future scenarios that have little economic support behind the evolution of wood product markets (13, 15, 16). Consequently, the future potential of the harvested wood carbon pool is poorly understood, even though it is now mandatorily included within current IPCC Good Practice Guidance. (Johnston and Radeloff 2019). . ., even under a best-case scenario, and when accounting for this gap, the global potential of HWPs as a carbon sink is minor and always <1% of emissions. (Johnston and Radeloff 2019)As (Mishra 2022) points out, if the building industry does begin substituting HWP for conventional building materials, the amount of timber being produced would have to grow by a substantial amount. Converting forested and other land to plantations to meet demand is problematic for several reasons, one of which is a decline in biodiversity.Here we assess the global and regional impacts of increased demand for engineered wood on land use and associated CO2 emissions until 21OO using an open-source land system model. We show that if 9O% of the new urban population would be housed in newly built urban mid-rise buildings with wooden constructions, 106 Gt of additional C02 could be saved by 2100. Forest plantations would need to expand by up to 149 Mha by 210O and harvests from unprotected natural forests would increase.In 2020, the plantation area was 132 Mha (i.e., 8% of global cropland area (1595 Mha) and only 4% of global natural forest area (3629 Mha)), but it likely contributed more than 33% to global industrial roundwood production.. . ., establishing new plantations has both land-use implications (in terms of competition for land) and negative biodiversity impacts when natural ecosystems are replaced.A recent study quantified the building sector side of avoided carbon emissions when using timber as construction material. While that study highlights the mitigation potential of using engineered wood as construction material, it assumes that the increased demand for construction" grade engineered wood can potentially be supplied from the world's forests based on historical trends and published projections of future biomass availability.Our future projections highlight that forest plantation areas would need to expand by more than 1OO% in 21OO compared to 2O2O in the BAU (business as usual) scenario even without additional construction wood demand. Emphasis addedEven though additional engineered wood demand for construction purposes can be met by utilizing forest plantations, this would result in a lot of new forest plantations being established on existing unprotected natural forests (Supplementary Figs. 4,5) and non-forest natural vegetation. Natural This encroachment in natural forests is feasible . . . but in reality, might entail losses in biodiversity and soil carbon.. . ., we see most of the reduced carbon emission benefits only after mid-century.In addition, producing timber for buildings made from wood results in higher forest regrowth over time due to the establishment of new forest plantations on otherwise less productive land as well as a reduced share of production being sourced from natural vegetation, resulting in net carbon uptake rather than release. However, the increasing risk of forest disturbances under climate change with a negative impact on natural forest carbon stocks, as well as plantation productivity and wood quality, could affect the regrowth potential.To compensate for restrictions in biomass removal from natural forests, a higher amount of timber production can come from highly managed forest plantations. However, higher harvest from forest plantations is also associated with declining biodiversity.Forest growth curves also dictate the relationship between time and estimated carbon sequestration in trees. Net carbon emissions in the first cycle of newly established forest plantations depend on upfront emissions from land conversions and subsequent carbon sequestration modeled via changes in age-class structure-a dynamic that is likely sensitive to the choice of growth curves. A flatter growth curve at the beginning of forest growthwould result in a longer time needed to capture back the carbon emissions from the first cycle of forest plantation establishment. Alternatively, the realization of a steeper growth curve in a forest would likely result in earlier recouping of carbon emissions from the first cycle of newly established forest plantations. In this study, we did not perform a sensitivity analysis of the changes in growth curve assumptions.Increased forest harvesting would need to be ensured as part of an overall commitment to sustainable forest management and governance.[hellip] the land expansion needed for forest plantation in the highly engineered wood demand scenarios is unlikely to benefit biodiversity.These assumptions ignore the biodiversity impacts of increases in harvest levels. These studies also assume that if forests can be managed in a way that the harvesting rate is no more than additional increments, then, the overall forest management is sustainable, neglecting effects on other ecosystem services and biodiversity.BiofuelsMany claims are made that using wood for bioenergy is carbon neutral. The most thorough research shows those assertions to be false including a study by (Dugan 2018).None of our results supported the notion that using wood for bioenergy is "carbon neutral." Rather, our study shows that over this 32 years period increasing harvests or allocating more harvested wood for bioenergy does not result in a sufficient substitution benefit to compensate for the increase in emissions from the immediate combustion of biomass or the reduction in ecosystem C stocks and uptake, as described elsewhere.The declaration of carbon neutrality for biomass burning is a policy assumption that does not reflect the actual impacts and timing of bioenergy emissions on the atmosphere (Sathre et al 2010; Skog 2008; Kull et al 2011). It is often made to encourage the replacement of fossil fuels with bioenergy. Here we evaluate the net impacts on the atmosphere as well as the timing of both emissions and removals, which indicate that in the relatively short-term (up to 32 years in this study), bioenergy use may result in increased carbon emissions.Burning wood for energy usually produces more emissions (C) than coal. In addition, recovery of all emissions by future growth takes longer than the age of the harvested forest.Burning wood for energy produces as much or more emissions as burning coal, so it is not an effective climate mitigation solution (Law et al 2018; Hudiburg et al 2011, 2019; Sterman et al 2018). It always takes longer for the forest to regrow and recover all of the carbon released than the age of the forest that was harvested (Schlesinger 2018). It is incorrect to describe burning of wood for energy as carbon neutral, because it increases carbon emissions now, when we can least afford such increases to the atmosphere. Alternatively, if the original trees continued to grow, without logging, there would be more than twice as much carbon in the trees and that much less in the atmosphere. (B. E. Law, The Status of Science on Forest Carbon Management to Mitigate Climate Change 2020)Even sustainable forest management does not support the use of wood for bioenergy.. . . wood bioenergy harvest worsens climate change even if the harvested forests are managed sustainably, because the average total stock of carbon on the land is lower than prior to harvest, and the carbon lost from the land is added to the atmosphere, worsening climate change (Sterman et al 2018). (B. E. Law, Creating Strategic Reserves to Protect Forest Carbon and Reduce Biodiversity Losses in the United States 2022)Two points are often ignored when endorsing the use of wood for bioenergy:First, the difference between eventual carbon neutrality and climate neutrality.Eventual carbon neutrality does not mean climate neutrality. The excess CO2 from wood bioenergy worsens global warming immediately upon entering the atmosphere. The harms caused by that additional warming are not undone even if regrowth eventually removes all the excess CO2. Global average surface temperatures will not immediately return to previous levels and may persist for a millennium or more (Solomon et al 2009). (B. E. Law, Creating Strategic Reserves to Protect Forest Carbon and Reduce Biodiversity Losses in the United States 2022)Second, climate neutrality and the carbon debt payback time.The time between the combustion of wood and the potential, eventual removal of that excess CO2 by regrowth is known as the carbon debt payback time to the atmosphere (Mitchell et al 2012). For forests in the eastern U.S., which supply much of the wood for pellet production and export, carbon debt payback times range from many decades to a century or more, depending on the species and climate zone (Sterman et al 2018a, 2018b).Carbon debt payback times are increased because harvesting wood from growing forests also prevents the CO2 removal that would have occurred had trees not been harvested and burned. (B. E. Law, The Status of Science on Forest Carbon Management to Mitigate Climate Change and Protect Water and Biodiversity 2022)Discounting those two inconvenient points has allowed continued support for using wood to produce energy and for the U.S. government to require federal agencies to consider forest bioenergy as carbon neutral. (Hudiburg 2019)The most recent global carbon budget estimate indicates that land-based sinks remove 29% of anthropogenic emissions (including land use change) with a significant contribution from forests (Le Qu[eacute]r[eacute] et al 2018). However, none of the agreements or policies (IPCC 2006, NRCS 2010, Brown et al 2014, Doe 2017, EPA 2017, Duncan 2017) provides [sic] clear and consistent procedures for quantitatively assessing the extent forests and forest products are increasing or reducing carbon dioxide concentrations in the atmosphere. . . . Methods are often in disagreement over the wood product Life Cycle Assessment (LCA) assumption of a priori carbon neutrality, where biogenic emissions from the combustion and decomposition of wood is ignored because the carbon released from wood is assumed to be replaced by subsequent tree growth in the following decades (EPA 2016). Despite a multitude of analyses that recognize that the assumption is fundamentally flawed (Harmon et al 1996,Gunn et al 2011, Haberl et al 2012, Schulze et al 2012, Buchholz et al 2016, Booth 2018), it continues to be used in mitigation analyses, particularly for wood bioenergy.The United States government currently requires all federal agencies to count forest bioenergy as carbon neutral because the EPA assumes replacement by future regrowth of forests somewhere that may take several decades or longer (EPA 2018). While it is theoretically possible that a replacement forest will grow and absorb a like amount of CO2 to that emitted decades or a century before, there is no guarantee that this will happen, and the enforcement is transferred to future generations. In any rational economic analysis, a benefit in the distant future must be discounted against the immediate damage associated with emissions during combustion. Furthermore, the goal for climate protection is not climate neutrality, but rather reduction of net GHGs emissions to the atmosphere to avoid dangerous interference with the climate system. Allowing forests to reach their biological potential for growth and sequestration, maintaining large trees (Lutz et al 2018), reforesting recently cut lands, and afforestation of suitable areas will remove additional CO2 from the atmosphere. Global vegetation stores of carbon are 50% of their potential including western forests because of harvest activities (Erb et al 2017). Clearly, western forests could do more to address climate change through carbon sequestration if allowed to grow longer.ConclusionClimate scientists have established that Earth is experiencing global warming driven by the continuing increase of greenhouse gases in the atmosphere. To moderate the consequences of the rapidly warming climate, fossil fuel emissions must be drastically reduced or eliminated and greenhouse gases, especially atmospheric carbon dioxide (CO2) and methane (CH4), must be reduced as quickly as possible.Scientific research and studies have shown that forest ecosystems provide wildlife habitat, help maintain biodiversity, deliver and store clean water, sequester and store carbon, and that forests should not simply be managed as tree farms. Research for this paper overwhelmingly indicated that forest management, as practiced today, decreases a forest's ability to sequester and store carbon. Management activities that include thinning and logging to change wildfire behavior, make wildfire suppression easier, or to reduce future insect mortality and disease, are counterproductive in the long term and reduce a forest's capacity to sequester and store carbon.Although forest soil stores approximately half of a forest's carbon, soil research is infrequently included in the analysis of management practices. Ignoring every impact of management activities (i.e., logging, thinning, salvage logging, harvesting for bioenergy production, pile burning, prescribed burning) is likely to reduce a forest's above- and below-ground C storage and, by disregarding the significance of mycorrhizal fungi, negatively impact future tree growth and forest health.Forest managers' focus emphasis on the economic value of tree harvesting overlooks how optimizing economic benefits reduces a forest's ability to sequester and store carbon. Given Earth's rapidly warming climate, research for this paper strongly suggests that forest management should abandon its focus on extraction activities (i.e., logging and thinning) and emphasize improving the ability of forests to sequester and store carbon.ReferencesBaker, W. L., and M. A. Williams. 2015. "Bet-hedging dry-forest resilience to climate-change threats in the western USA based on historical forest structure." Frontiers in Ecology and Evolution 2: 7. https://www.frontiersin.org/journals/ecology-and-evolution/articles/10.3389/fevo.2014.00088/full.Bartowitz, K. J. et al. 2022. "Forest Carbon Emission Sources Are Not Equal: Putting Fire, Harvest, and Fossil Fuel Emissions in Context." Frontiers in Forests and Global Change 5: 1-11. Accessed 2022. https://www.frontiersin.org/articles/10.3389/ffgc.2022.867112/full.Batllori, E. et al. 2020. "Forest and woodland replacement patterns following drought-related mortality." 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