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Perspective

Creating Strategic Reserves to Protect Forest Carbon and Reduce Biodiversity Losses in the United States

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Abstract: This paper provides a review and comparison of strategies to increase forest carbon, and reduce species losses for climate change mitigation and adaptation in the United States. It compares forest management strategies and actions that are taking place or being proposed to reduce wildfire risk and to increase carbon storage with recent research findings. International agreements state that safeguarding biodiversity and ecosystems is fundamental to climate resilience with respect to climate change impacts on them, and their roles in adaptation and mitigation. The recent Intergovernmental Panel on Climate Change report on impacts, mitigation, and adaptation found, and member countries agreed, that maintaining the resilience of biodiversity and ecosystem services at a global scale is "fundamental" for climate mitigation and adaptation, and requires "effective and equitable conservation of approximately 30 to 50% of Earth's land, freshwater and ocean areas, including current near-natural ecosystems." 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.

Keywords: carbon dioxide; biodiversity; preservation targets; climate mitigation; climate adaptation; deforestation proforestation

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1. Introduction

The climate is changing rapidly at an accelerating rate in every region of the planet. Immediate and sustained actions are needed to reduce dangerous and amplifying warming feedbacks. To avoid catastrophic, irreversible release of heat trapping methane and carbon dioxide, it is essential that natural land and ocean sinks remove and store substantially more atmospheric carbon dioxide to halt Arctic warming that is increasing over 3 times faster than the planetary average [1,2]. The next 10 to 30 years are a critical window for climate action, when severe ecological disruption is expected to accelerate [2–4]. Analysis of country-based pledges to reduce emissions in the nationally determined contributions (NDCs) suggests that emissions reductions should increase by 80% above the combined NDCs to keep temperature increases below the proposed 2 °C limit [5], and even greater reductions are required to remain below 1.5 °C. It is worth noting that these limits are warmer than the current temperature increase of 1.1 °C, meaning that the consequences for all climate-related changes will be more severe if those limits are reached or breached.

Forests play an important role in storing carbon, along with oceans, wetlands, and peatlands. Forests account for 92% of all terrestrial biomass globally, storing approximately 400 gigatons carbon [6]. Despite regional negative effects of climate change on the net amount of carbon removed from the atmosphere annually by land ecosystems, their removal of carbon dioxide from the atmosphere has remained fairly constant over the last 60 years at about 31% of emissions, with forests contributing the most [7]. Forests can play an important role in capturing and storing immense amounts of carbon. Reducing emissions from energy systems, deforestation, forest degradation, and other sources while increasing accumulation of carbon by natural systems are the primary means by which we will control atmospheric carbon dioxide (CO_2).

Here we present the status of science on forest management to mitigate climate change, and protect water and biodiversity in the United States, as well as the importance of Strategic Reserves to accomplish national and international goals of reducing biodiversity losses, and increasing the forest carbon reservoirs using natural climate solutions.

As discussed in more detail below, 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. This is why the 2021 report by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services and the Intergovernmental Panel on Climate Change (IPBES-IPCC) [8] stresses that climate change and biodiversity need to be examined together as parts of the same complex problem when developing climate mitigation and adaptation solutions [9,10].

The IPCC Assessment Report 6 confirms the findings of a growing body of research that maintaining ecosystem integrity and its biodiversity are essential to an effective response to a changing climate [1]. The Summary for Policy Makers, which is approved line by line by all IPCC member governments *including the United States*, summarizes current adaptation and mitigation climate science as follows:

"Summary for Policy Makers.D.4 Safeguarding biodiversity and ecosystems is fundamental to climate resilient development, in light of the threats climate change poses to them and their roles in adaptation and mitigation (very high confidence)."

"Summary for Policy Makers.D.4.1 Building the resilience of biodiversity and supporting ecosystem integrity can maintain benefits for people, including livelihoods, human health and well-being and the provision of food, fibre and water, as well as contributing to disaster risk reduction and climate change adaptation and mitigation." The formal definition of ecosystem integrity refers to the "ability of ecosystems to maintain key ecological processes, recover from disturbance, and adapt to new conditions."

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 [8] and policymakers or those implemented by land managers and industries, and recent research has quantified their effectiveness and inadequacies. The strategies include:

- Avoiding deforestation and forest degradation—keeping forests intact;
- Reducing carbon loss by increasing harvest intervals and decreasing harvest intensity;
- Carbon storage in long-lived forest products (e.g., in combination with shorter harvest intervals);
- Burning trees for bioenergy;
- Thinning to reduce fire risk or severity and thus carbon losses.

We provide a synthesis of literature on evaluation of these strategies, as well as the importance of protecting the many values of forests, including carbon accumulation, biodiversity, and water availability. We focus on two regions of the U.S., the Pacific Coast, and southeast regions, which account for about 45% of the total U.S. forests' living biomass and removals by harvest [11].

2. Strategies

2.1. Avoid Deforestation and Forest Degradation, and Decrease Harvest-Related Carbon Losses

Primary forests are defined as forests composed of native species in which there are no clearly visible indications of human activities and ecological processes have not been significantly disturbed [12]. Multiple values are found at higher levels in intact forests of a given type, including habitat for endangered species, water security, and accumulated forest carbon stocks that keep carbon out of the atmosphere, and provide moderation of air and surface temperature through evapotranspiration [13,14]. Only 7% of the forest area in the U.S. is considered intact, with the exception of the nearly 68,000 km^2 Tongass National Forest in southeast Alaska, of which about 20,000 km^2 is defined as productive old-growth. Most of its 900 watersheds are near natural conditions, and its carbon-rich rainforests have similar carbon densities to the Pacific Northwest U.S. rainforests [15–17]. It is the largest intact temperate rainforest in the world, yet logging of old-growth continues while the USDA is in the process of restoring the roadless protections. The 2001 Roadless Rule prohibits road construction and timber harvesting on almost 30 million hectares of inventoried roadless areas (IRAs) on National Forest System lands, and is intended to provide protection for multiple uses.

Federal lands managed by the U.S. Forest Service (FS), the National Forest System (NFS), and the Bureau of Land Management (BLM) are managed under a multiple use—sustained yield model [18,19]. The statute directs the agencies to "balance multiple uses of their lands and ensure a sustained yield of those uses in perpetuity" [20]. The forest management plans describe where timber harvesting may occur as well as measures of sustainable harvest levels. The balance of these uses on federal lands has been an ongoing point of contention with the public [20].

Most timber harvesting occurs on private lands [11], however, there is increasing pressure to allow more timber cutting on federal lands. In the Pacific Northwest (PNW), removals declined on public lands after the peak in the late 1980s [11], partly due to implementation of the Northwest Forest Plan on public lands that aimed to protect endangered species in old-growth forests. The result was a strong increase in forest carbon accumulation on public lands over the next 17 years, while private lands remained near zero carbon accumulation, accounting for losses due to wildfire and harvesting [21].

Most forests in the U.S. have been harvested multiple times, and many managed forests are harvested well before reaching maturity. As of 2014, 51% of timber land in the south was less than 40 years old compared with 20% in the north and 22% in the west. In contrast, 56% of northern timber land was more than 60 years old, compared with 27% in the south and 69% in the west [11]. Since then, harvest ages have decreased in some cases because of changes in forest products (e.g., increasing production of cross-laminated timber, wood for bioenergy), thinning to reduce wildfire risk or severity, or removals after fire or beetle kill. Consequently, forest carbon densities are much lower than their potential, and could accumulate much more carbon and avoid carbon emissions associated with harvest [22].

Evaluation of strategies to mitigate climate change showed that forests can store more carbon if the harvest interval is lengthened on private lands and harvest is reduced on public lands in Oregon (Figure 1) [15]. A comparison of strategies showed that reducing harvest by half on public forests to allow them to continue to accumulate carbon (cumulative net ecosystem carbon balance, NECB) while increasing harvest rotation age from 40 years back to 80 years in forests with relatively low vulnerability to drought and fire under future climate conditions contribute the most to increasing forest carbon and reducing emissions. Far less effective are reforestation—just one-third as much carbon accumulation—and lastly, afforestation—just one-tenth as much carbon accumulation—that can compete with land usage for agriculture and urban development. This finding is supported by a recent National Academy report on "Negative Emissions" or atmospheric CO_2 removal options that finds the potential for afforestation and reforestation in limiting atmospheric CO_2 to be modest [23].

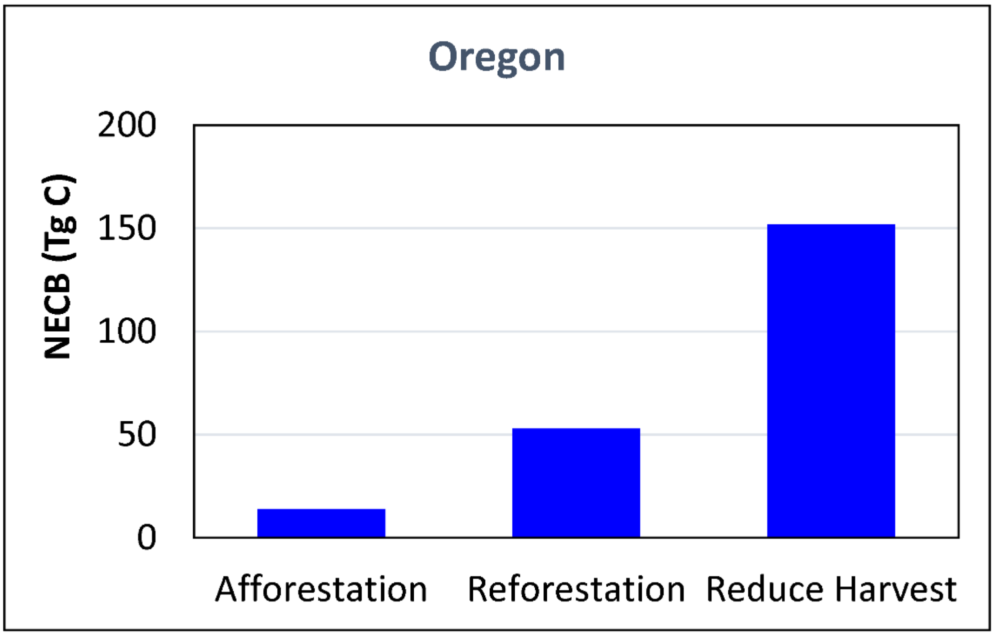

Figure 1. Land-use strategies to mitigate climate change across Oregon. Values on y-axis are cumulative change in net ecosystem carbon balance (NECB) from 2015 to 2100. Reduced harvest is a combination of restricted harvest by half on federal lands, and increased harvest intervals to 80 years on private lands. Data are from observation-based modeling [15].

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 [24]. 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 [25]. 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^{-1} yr^{-1} [26].

Thus, temperate forests with high carbon and lower vulnerability to mortality have substantial additional capacity for climate mitigation. On a global level, it is estimated that forests could hold twice as much carbon as they currently do if managed differently [27]. While planting trees is desirable, that will contribute relatively little to carbon accumulation out of the atmosphere by 2100 compared to reducing harvest (See Figure 1). For example, if the Bonn Challenge of restoring 350 Mha by 2030 is given to natural forests, they would store an additional 42 Pg C by 2100, whereas giving the same area to plantations would store only 1 Pg C [15,28].

The potential for additional carbon accumulation is also being degraded by current management practices [29]. It was estimated that the "current gross carbon sink in forests recovering from harvests and abandoned agriculture to be −4.4 GtC/y, globally" [30]. This is more than the current difference between anthropogenic emissions and land and ocean annual accumulation out of the atmosphere (3.4 GtC/y) [7].

Mature and old forests generally store more carbon in trees and soil than young forests, and continue to accumulate it over decades to centuries [15,16,25] making them the most effective forest-related climate mitigation strategy. For example, restricting harvest by half on federal forests and changing the harvest cycle to 80 years across Oregon would increase forest carbon stocks 118 Tg C by 2100 [15,16,25]. Converting mature and older forests to younger forests results in a significant loss of total carbon stores, even when wood products are considered [31,32]. For example, a comparison of carbon stored in an unharvested versus harvested mature forest using the Forest-GHG life cycle assessment model to track harvested carbon from forest to landfill [31] shows that the unharvested forest has a much higher carbon density 120 years later, even when carbon in wood products is summed with the post-harvest carbon storage (Figure 2).

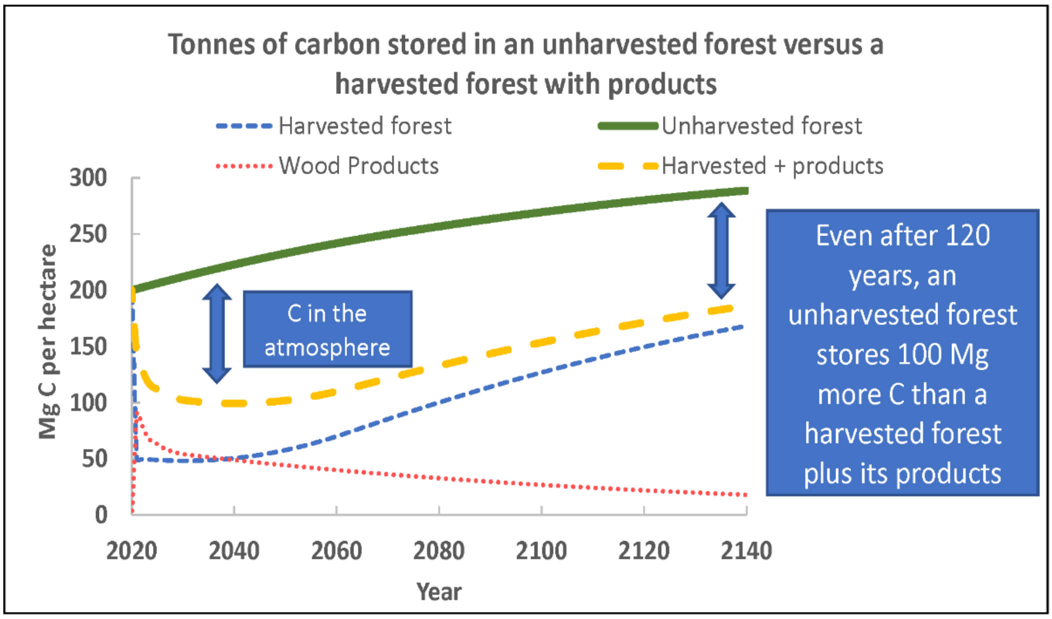

Figure 2. A mature forest with a carbon density of 200 tons of carbon per hectare (green line) is harvested (blue line) in 2020. This results in an immediate reduction of live tree carbon stocks. Approximately half of the aboveground carbon is removed and taken to the mills (as wood) while the other half remains behind in slash piles (leaves, bark, branches, etc.) and in the dead belowground roots. The slash is burned on-site and the carbon is immediately emitted to the atmosphere. The roots decompose over the next few decades, emitting carbon to the atmosphere. The carbon taken to the mill as wood is processed into short- and long-term wood products (red line), that decay over years to centuries, eventually returning the carbon to the atmosphere. Estimates comparing the carbon benefits of wood products to alternative materials have been found to overestimate the benefit by factors of between 2- and 100-fold by not counting the full life cycle carbon and the shorter durability of wood relative to alternative materials [33].

2.2. Harvesting Forests for Bioenergy Production

Utilizing wood biomass as a substitute for coal *increases* CO_2 emissions and *worsens* climate change for many decades or more [34]. Meeting U.S. national emissions reduction goals requires net emissions to drop by approximately 50% by 2030, reach net zero by 2050, and be net negative beyond 2100 [2,4].

Although wood and coal release comparable amounts of carbon dioxide per unit of primary energy [35], wood chips and pellets burn less efficiently. For example, a 500-megawatt power plant burning wood pellets emits an estimated 437,300 tons of CO_2-C annually, whereas the same plant burning coal would emit 392,000 tons/year [36]. The situation is worse if wood displaces other fossil fuels: wood releases about 25% more CO_2 per unit of primary energy than fuel oil, and about 75% more CO_2 than fossil (natural) gas [35]. Further, greenhouse gas emissions from the wood supply chain exceed those of the coal supply chain: Approximately 27% of harvested carbon equivalent is used to produce dry pellets [37], while coal processing adds just about 11% to emissions [38]. Therefore, the immediate impact of wood bioenergy is an increase in CO_2 emissions, creating a "carbon debt", even when wood displaces coal, the most carbon intensive fossil fuel. The harvested forests can regrow, repaying the debt, but regrowth is uncertain and takes time.

Regrowth takes time: The time between the combustion of wood and the potential, *eventual* removal of that excess CO_2 by regrowth is known as the carbon debt payback time [39]. For forests in the eastern U.S., which supply much of the wood for pellet production and national and international export, carbon debt payback times range from many decades to a century or more, depending on forest age at harvest, species, and climate zone [38,40].

Carbon debt payback times are longer in the young forests prevalent in the U.S. because harvesting wood from growing forests also prevents the CO_2 removal that would have occurred had trees not been harvested and burned [41]. If a 40-year-old forest was harvested and burned, releasing its carbon immediately to the atmosphere, under ideal conditions, it would take another 40 years to remove the added carbon from the atmosphere and restore the initial carbon stocks in the regrown forest, known as "slow in, fast out" [42–44]. However, if not harvested, the same forests would have continued to accumulate significantly more carbon, thereby further reducing the amount in the atmosphere. Shorter rotation times between harvests for bioenergy leave the greatest amount of CO_2 in the atmosphere [40].

Forests of the southeastern and southcentral U.S. are the largest source of wood for commercial scale bioenergy, mostly for use in Europe. If allowed to continue growing (proforestation), they could remove significant additional atmospheric CO_2 and accumulate the additional carbon in trees and soils [22].

Note that 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 [38,40]. Moreover, reforestation following harvest of a diverse bottomland hardwood forest that provided habitat for multiple animal species would, in most cases, be converted to a pine monoculture plantation.

Eventual carbon neutrality does not mean *climate neutrality*. The excess CO_2 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 CO_2. Global average surface temperatures will not immediately return to previous levels and may persist for a millennium or more [45]. The Greenland and Antarctic ice sheets melt faster, sea level rises higher, accelerated permafrost thaw releases more methane, wildfires become more likely, storms intensify more, and extinction is greater than if the forest had not been harvested and the wood had not been burned [45]. Recent simultaneous temperature spikes of tens of degrees Celsius in the Arctic and Antarctica demonstrate that unprecedented warming signals are already occurring, resulting in some changes, such as sea-level rise, that are irreversible for centuries to millennia [1]. Even eventual full forest recovery and carbon removal will not replace lost ice, lower sea level, undo climate disasters, or bring back communities lost to floods or wildfires.

2.3. Thinning to Reduce Fire Risk or Severity and Carbon Loss

2.3.1. Broad-Scale Thinning to Reduce Fire Severity Conflicts with Climate Goals

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 [42,46–49]. 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 [50]. For example, thinning in a young ponderosa pine plantation showed that removal of 40% of the tree biomass would release about 60% of the carbon over the next 30 years [51]. Regional patchworks of intensive forest management have increased fire severity in adjacent forests [49]. Management actions can create more surface fuels. Broad-scale thinning (e.g., ecoregions, regions) to reduce fire risk or severity [52] results in more carbon emissions than fire, and creates a long-term carbon deficit that undermines climate goals.

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 [53]. The potential effectiveness of treatments lasts only 10–20 years, diminishing annually [53]. Thus, the preemptive actions to reduce fire risk or severity across regions have been largely ineffective.

Effective risk reduction solutions need to be tailored to the specific conditions. In fire-prone dry forests, careful removal of fuel ladders such as saplings and leaving the large fire-resistant trees in the forest may be sufficient and would have lower carbon consequences than broad-scale thinning [54]. The goals of restoring ecosystem processes and/or reducing risk in fire-prone regions can be met by removing small trees and underburning to reduce surface fuels, not by removal of larger trees, which is sometimes done to offset the cost of the thinning. With continued warming and the need to adapt to wildfire, thinning may restore more frequent low-severity fire in some dry forests, but could jeopardize regeneration and trigger a regime change to non-forest ecosystems [53].

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 [21,46]. 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 [55,56]. These findings are consistent with field studies on Oregon's East Cascades wildfires and the large Biscuit Fire in southern Oregon [57,58].

To summarize, 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, and California's fire emissions were a few percent of its fossil fuel emissions [59]. In the conterminous 48 states, harvest-related emissions are 7.5 times those from all natural causes [60]. 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.

2.3.2. Change Focus from Broadscale Thinning to the Home Ignition Zone

Over the past century, public agencies have been responsible for managing fire risk and protecting communities, however, their focus has been on suppression, fuel reduction, and prevention. Yet, of all the ignitions that crossed jurisdictional boundaries, more than 60% originated on private property and 28% in national forests [61]. These findings are in stark contrast to the common narrative that wildfires start on remote public land and then move into communities [62].

Hardening home structures in areas with high risk of wildfires such as the wildland-urban interface has been found to be the most effective means to reduce property damage from wildfires [63]. Many rural homes use propane tanks that explode from the intense heat. Safer energy options for homeowners would reduce the spread from house to house and the loss of the structures. Community safety experts and wildfire risk managers indicate that focus should be on addressing the home ignition zone by using fire-resistant designs, more intensive fuel reduction close to buildings, and preventing new developments in high fire-risk areas [64]. Incentives are misaligned because zoning and approval of building locations are functions of local governments, but responding to fires, and shouldering those costs, are the responsibility of state and federal agencies. Additionally, a large number of the most destructive fires have been ignited by poorly maintained powerlines [65]. Buried lines and better maintenance could reduce the frequency of wildfires.

2.3.3. Post-Fire Harvest versus Natural Regeneration

After fires, the remaining live and dead trees in the burn area and those on the periphery provide seed sources for natural regeneration [66]. Fires also provide ash which can act as a natural fertilizer, providing macro- and micronutrients for regrowth. Natural regeneration allows germination of genetic- and species-diverse seeds, and resprouting of shrubs that provide important habitat as forests recover. The diversity of early successional species also increases the resilience of the ecosystem to future disturbance, and accumulates additional carbon [67]. Natural and managed regeneration failures have occurred, particularly in dry regions [67–69], but here we are referring to the diversity of seed stock in natural regeneration compared to planting of less diverse seedling sources. Although there is enthusiasm about participating in reforestation, tree planting must be done carefully to ensure appropriate species selection for specific sites, whereas natural growth has more likelihood of re-establishing local biodiversity [67].

The complex early seral forest habitats that develop after high severity burns are important to a broad range of wildlife [70]. Post-fire harvest and felling of live and dead trees can harm soil integrity, hydrology, natural regeneration, slope stability, and wildlife habitat [71]. Large standing dead, live yet possibly dying, and downed trees help forests recover and provide habitat for more than 150 vertebrates in the PNW [72].

In burned watersheds, post-fire logging worsens conditions that have resulted from a century of human activity [73,74] and impedes the rate of recovery. In sum, post-fire treatments can cause a significant loss of ecosystem services [75].

3. Solutions

To mitigate climate change and avoid additional irreversible changes, we must reduce energy consumption through greater end-use efficiency gains and shift to carbon-free energy sources (e.g., solar and wind) [76], and simultaneously increase removal and accumulation of additional carbon from the atmosphere in forests, wetlands, and soils.

Global studies have identified areas for protection of intact forests that would stem biodiversity loss and prevent land conversion to other uses [77,78]. A recent study suggests assessment of ecosystem integrity represented by faunal intactness (no loss of species), habitat intactness, and functional intactness (no reduction in faunal densities below ecologically functional densities) [1]. However, global analyses can miss important local to regional ecological features that affect species and thus, the potential for protections. A global meta-analysis showed that most vulnerable bird species need large intact forests, although relatively small fragments can still have substantial biodiversity value if protected at the highest levels (IUCN categories I-VI) [79]. To address this issue, the International Union for Conservation of Nature (IUCN) developed a policy [80] for defining forests of conservation value:

"While primary forests of all extents have conservation value, areas of greater extent warrant particular attention where they persist, as they support more biodiversity, contain larger carbon stocks, provide more ecosystem services, encompass larger-scaled natural processes, and are more resilient to external stresses. The significance of large areas of primary forests has been highlighted by the global mapping of Intact Forest Landscapes (IFL) greater than 500 km^2 in extent. While suitable for many purposes, other thresholds may be more suitable at regional and national levels that reflect local ecological factors." (IUCN Policy Statement on Primary Forests, https://www.iucn.org/sites/dev/files/content/documents/iucn_pf-ifl_policy_2020_approved_version.pdf, accessed on 22 April 2020).

Much focus has been on protecting some notable primary forests [81] such as the Amazon, but that should not distract our attention from the need to retain significant intact forests within North America. There is more carbon stored in the world's temperate and boreal forests combined than in all remaining tropical forests [81]. There are ecosystems in many ecoregions that meet the conditions for protecting half of forestlands [82]. Bird populations are good indicators of ecosystem integrity. A net population decline of 2.9 billion birds in North America occurred between 1970 and 2017, of which forest- dependent species accounted for over one-third of the total, indicating a loss of insects and rapid recent degradation of forest ecosystem integrity [83,84].

Areas in the lower 48 states with high concentrations of imperiled forest- and non-forest species with small ranges in the west and east should be considered for protection (Figure 3) [85].

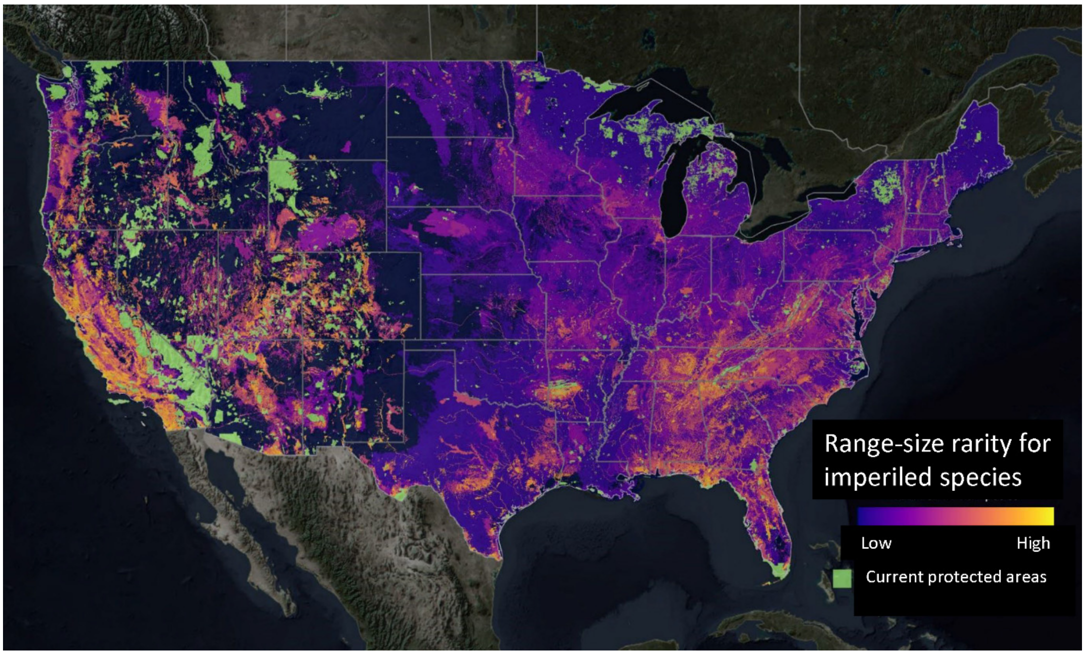

Figure 3. Summed range-size rarity of forest and non-forest species in the lower 48 states that are protected by the Endangered Species Act and/or considered to be in danger of extinction. Species include vertebrates (birds, mammals, amphibians, reptiles, freshwater fishes), freshwater invertebrates, pollinators, and vascular plants. High values (yellow) are areas where species with small ranges (and thus fewer places where they can be conserved) are likely to occur; the presence of multiple imperiled species contributes to higher scores. (Image produced by NatureServe; https://livingatlas.arcgis.com, accessed 21 April 2022).

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. The 2022 IPCC AR6 report stated that "Recent analyses, drawing on a range of lines of evidence, suggest that maintaining the resilience of biodiversity and ecosystem services at a global scale depends on effective and equitable conservation of approximately 30% to 50% of Earth's land, freshwater and ocean areas, including currently near-natural ecosystems (high confidence)." Continuing commercial timber harvest on a portion of the remaining public lands and tens of millions of hectares of private lands would continue to adequately supply a sustainable forestry sector.

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 [86]. Discontinuing or greatly reducing this practice would be an important climate mitigation strategy.

High carbon forests in the western U.S. are highly biodiverse ecosystems that store and provide water to millions of people and to major agricultural regions, and are more resilient to climate change [9]. The PNW and Alaska stand out as having the largest mature and old forests with immense carbon stores and high biodiversity that meet the IPCC criteria of meriting protection to remove significant additional carbon from the atmosphere. A majority of these areas are on public lands with the potential for permanent protection consistent with the highest international standards, and could be complemented with additional protections on private and indigenous lands [87]. These forests are critical for greater future carbon accumulation, and are an essential source of clean drinking water [9]. Forests dominate the drinking water supply in the U.S. that must be protected at the source [88,89]. For example, forests account for almost 60% of the most important areas for surface drinking water in the western U.S., yet only about 19% are protected at the highest levels. Other regions of the U.S. such as the southeast host some of the greatest biodiversity on the continent, and require protection for their forest carbon, biodiversity, and water.

Across the eleven western U.S. states, a framework was applied to prioritize protection of high carbon and biodiversity forest areas to meet the 30 × 30 and 50 × 50 preservation targets (Figure 4). Out of 92.5 Mha of forestland in the region, 14% is currently protected at the level equivalent to wilderness areas, IUCN classification Ia to II, and 5% is protected at IUCN classifications III to VI, which allows practices that degrade existing natural communities, such as road building and suppression of natural disturbances [90]. To achieve 30% protection of forest area by 2030, an additional 10 Mha would need to be protected at these levels. To meet the 50% target by 2050, an increase of 29 Mha is required. The analysis examined, removing from consideration, areas that are at high risk of mortality from wildfire or drought under future climate conditions (Figure 5) [91] to determine if there was sufficient qualifying area to protect. The prioritization used an ecoregion approach [82] to determine relative importance for protection of biodiversity and/or carbon within each ecoregion. Ecoregions are delineated based on similarity of a range of abiotic and biotic characteristics (topography, climate, soils, vegetation), e.g., EPA Level III [92]. Ecoregion-based conservation was evaluated in a range of habitats, and is recognized as a strong basis for the need to conserve about half of each region [82]. A similar framework could be applied in other regions, with additional data such as species endemism, if available.

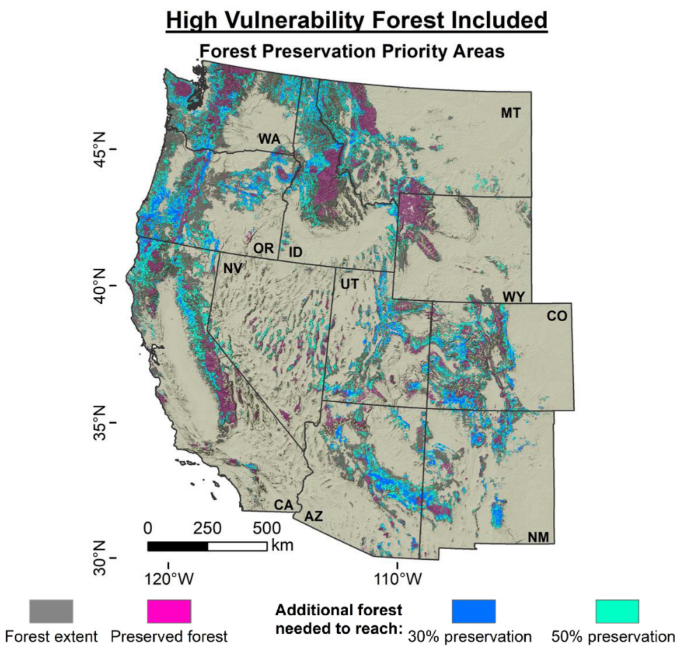

Figure 4. Forestlands that are currently preserved, and additional areas identified as high priority for protection of biodiversity and forest carbon for climate mitigation across the western U.S. Adapted from [5].

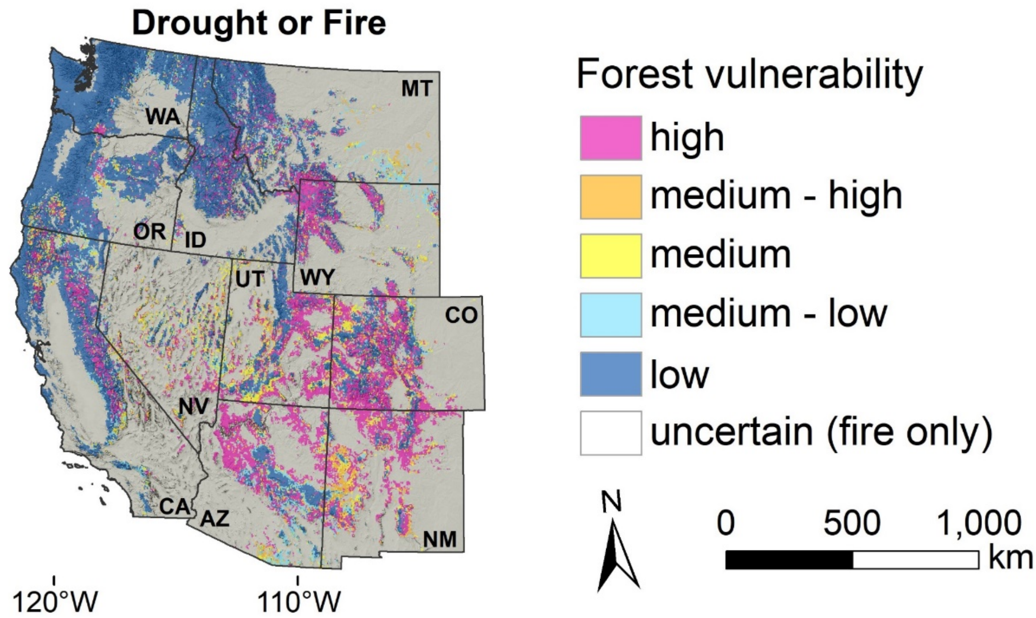

Figure 5. Vulnerability of forestlands to either drought or fire under future climate scenarios to year 2050. Adapted from [83].

The strategic reserves defined within each ecoregion would protect carbon, water, and biodiversity, and recognize the value of forested landscapes that are diverse in structure and function. Across the climate gradient from mesic to drier ecoregions, portions can be impacted by wildfire, but they are still important to protect their biodiversity, allowing species to persist (e.g., in refugia), migrate, and reorganize with a changing climate. An example is the Klamath Mountains ecoregion in Oregon and California, which has high biodiversity partly because of its unique geology. It is one of the top four temperate coniferous forests in species richness globally. Its vulnerability to forest fires should not disqualify it from protecting the rich diversity of plant and animal species from human degradation [70].

4. Conclusions

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" [93]. Many of the existing forest management practices allegedly 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 CO_2 to the atmosphere than fossil fuels. Its use is based upon a mistaken assumption that it is 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.

Climate change mitigation and biodiversity protection is an essential component of forest management decision-making. To avoid dangerous anthropogenic interference with the climate system, provide water security, and stem biodiversity losses, permanent Strategic Climate and Biodiversity Reserves need to be established quickly, and their integrity monitored and maintained.

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