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Review

Managing Moist Forests of the Pacific Northwest United States for Climate Positive Outcomes

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Abstract: The moist forests of the Pacific Northwest United States (PNW) are among the most naturally carbon rich ecoregions in the world. However, regional in-forest carbon storage levels are currently well below ecological potential. Recent climate policy proposals have renewed and deepened debates over forest sector climate strategies. This paper begins with a review of regionally applicable forest carbon life cycle assessments (LCAs) in an effort to provide some clarity around how these studies are conducted, and why their results may vary. The review highlights the importance of assumptions made during carbon accounting across the wood product lifespan and how the inclusion or exclusions of variables, such as product substitution and leakage, influence study results and subsequent management recommendations. Next we discuss the influence of climate change on forest management and planning. We conclude with a review of regional-specific factors to consider when developing optimal forest climate strategies in the moist forests of the PNW. These strategies include, but are not limited to; extending harvest rotations, shelterwood and select tree harvests (in lieu of full harvest), and managing forests for increased structural, age, and species complexity.

Keywords: forest carbon; Pacific Northwest; Douglas fir; life-cycle assessment; substitution; climate smart forestry

1. Introduction

Forests are a critical aspect of the global carbon cycle, sequestering ~30% of global carbon emissions over the last several decades [1,2]. In the U.S., forest land and wood products are a substantial carbon sink, representing over 90% of total terrestrial carbon storage [3]. In 2011, forests and wood products sequestered and stored an estimated 16% of the United States' annual carbon emissions [3]. The U.S. Environmental Protection Agency (EPA) revised this estimate down to a more modest, but still substantial 10% of national emissions in 2016 [4]. However, current and expected trends in forest conversion, degradation, disturbance, and mortality have the potential to shift forests from being the countries' largest carbon sink to being a potential net source of emissions [4,5].

Conversely, recent studies evaluating the potential for additional emission reductions from land-based activities such as improved forest management (IFM) (i.e., improving stocking through; variable retention harvesting, reductions in the size of clear cut openings, extending tree rotations, retaining a higher residual volume at harvest), found that such actions may have a substantial role to play in reducing emissions [6,7]. At the global scale, increasing the number and size of trees (reforestation, avoiding forest loss, and better forestry practices) could cost-effectively remove 7 billion tons of carbon dioxide annually by 2030, the equivalent of removing 1.5 billion gasoline-powered cars from operation [7]. Improved forest management practices may represent the most significant and cost effective land based climate change mitigation strategy in the U.S. [7]. However, the scale and pace at which these practices would need to be deployed to achieve such greenhouse gas (GHG) reductions seems unlikely under current economic and regulatory conditions.

'Cap and trade' systems and various forms of carbon taxation have been proposed and adopted throughout the world as a way to price GHG emissions, with similar forms of emission credit trading now dating back thirty years in the U.S. [8]. California and Quebec have passed 'cap and trade' legislation creating a market for carbon that is now linked through the Western Climate Initiative.

Recent legislative proposals to price GHG pollution in the Pacific Northwest of the U.S. (PNW) have included a carbon tax in Washington State and a 'cap and invest' bill in Oregon. If passed, such legislation could have important implications for forest management. Forest carbon offset projects and the investment of other revenues created by the auctioning of emission allowances are being promoted as strategies to incentivize IFM and secure important conservation co-benefits [9].

On the surface, this would appear to be a winning strategy. The West Cascades and Coast Range are among the most naturally carbon rich ecoregions in the world due to the moist temperate forests they contain [10,11]. Yet, research indicates in-forest carbon storage levels are currently well below ecological potential in these regions [12–14]. The difference between ecological potential and socio-political reality highlights the fact that forest management decisions are driven by a combination of dynamic, interwoven factors simultaneously playing out at a global, local, and inter-personal scale. Policy makers and land managers face the challenging task of understanding and balancing these factors when undertaking large-scale land management planning and policy design, with broad implications for common interest outcomes such as socio-economic well-being and climatic stability.

Debate remains about what forest management practices and wood products should be encouraged to achieve optimal climate outcomes. While it is agreed that managing for longer rotations and older, more diverse forest conditions would enhance in-forest carbon storage levels [15–17], securing climate positive outcomes requires consideration of the system level (i.e., the lifecycle of forest and wood product carbon pools) impacts of such actions [18,19].

Life cycle assessment (LCA) is an internationally standardized methodology used to evaluate such system level impacts by "quantifying the emissions, resources consumed and environmental and health impacts" associated with a given service or product system [20]. Life cycle assessment methods have been employed to illuminate how carbon flows through forests and wood products. The results of these assessments can vary significantly depending on inputs, assumptions, and accounting methods. The range of results has led to some confusion regarding forest sector emissions and optimal management strategies.

Thus, we begin this paper by reviewing forest carbon LCAs with an emphasis on assessments conducted in the PNW to clarify how these studies are conducted, and why their results may vary. Next, we discuss the influence of climate change on forest management strategies, including IFM, in the region. We then conclude with a review of regional-specific factors to consider when developing optimal forest climate strategies in the moist forests of the PNW.

2. Forest Carbon Life Cycle Accounting Considerations and Areas of Scientific Debate

Strategies to increase carbon sequestration and storage are ultimately attempting to address the global phenomenon of climate change by decreasing atmospheric concentrations of GHGs. Simply increasing carbon stores on one forest, or even within a single region, does not necessarily ensure this goal will be met [19,21–23]. The same may be said of regionally isolated forest management regulations or incentive programs to the extent that such strategies lead to increased harvesting and carbon loss in other regions (i.e., leakage).

Using life cycle assessment methodology to track forest carbon may enable decision makers to evaluate management impacts based on a more complete understanding of carbon transfer within regional forest sectors. As with any analysis, the factors that one chooses to include or exclude can have a powerful effect on results. Complete analysis must include important on-site (in-forest biomass and/or soil) and off-site (wood post-harvest) carbon pools, as well as the flux between these pools over time. Off-site factors to consider are leakage, substitution, and fossil fuel displacement.

Viewing forest management decisions or policy effects through appropriate geographic scales and time-frames is critical to understanding the net climate effect, particularly when analyzing numerous forest management and wood product pathways and the influence of policy [24]. In this section, we present a consolidated review of variables of how LCA studies incorporate important variables.

2.1. On-Site Forest Carbon Pools

On-site forest carbon pools include above and below ground carbon found within a forest. To obtain a comprehensive picture of carbon transfer in a forest ecosystem, both pools should be considered as they can be affected differently by natural cycles and management decisions. Above ground carbon pools, consisting of live and dead trees, downed woody material, and forest floor vegetation and detritus, may be significantly more effected by management actions than below ground carbon pools and are thus most available to shift from on-site to off-site pools.

Globally, soil carbon is the largest terrestrial carbon pool and the effects of forest management on soil carbon warrant continued study. Current knowledge suggests that in addition to being less dramatically effected by management actions, below ground carbon pools are more difficult to measure and are treated inconsistently in current forest life cycle accounting. Many studies opt to omit this pool because net-changes are considered small and/or difficult to measure [25–27] or because soil data is absent from relevant modelling tools [28,29]. Analyses that include soil carbon often differ in depth measured, with subsequently varying results regarding management impacts.

A global meta-analysis documented an average soil carbon loss of 8% due to harvest [30]. Lippke [25] suggests that most of this loss can be mitigated through specific management practices such as adequate coarse and fine woody debris left on site. Assumptions in LCA accounting regarding soil quality, fertilization rates [31], and disturbance [32], will affect outputs and subsequent management recommendations.

2.2. Off-Site Forest Carbon Pools

Methods of accounting for carbon stored in wood product pools (i.e., off-site storage) has been a topic of much debate and some scientific disagreement. A review of relevant literature revealed that key considerations include: use and disposal of wood residuals produced throughout the product supply chain (at harvest via logging, at sawmills, and at secondary and tertiary wood processing facilities), mill and processing efficiency and utilization, wood product use, allocation, life span, substitution and fuel displacement, and material end-of-life assumptions [21,23,27,28,33–40].

2.3. Substitution

In off-site forest carbon accounting, the concept of 'substitution' attempts to quantify the emissions impact of using or not using wood products as opposed to some alternative material (e.g., steel, concrete, plastics, etc.). The inclusion or exclusion of emission gains/losses from substitution, as well as how they are calculated, can have a profound impact on the net carbon results of LCA analysis of wood products and subsequent timber management recommendations (see Table S1).

For example, Perez-Garcia et al. [36] achieved very different outcomes in their analysis due to the inclusion or exclusion of product substitution (Figure 1). The study used several models to analyze results from a life cycle assessment on housing construction to derive average annual carbon stores in simulated forests with characteristics similar to those in the west Cascades of the PNW. After 165 years, the scenario including the substitution of concrete and steel with wood and the shortest harvest rotation cycle accumulated the most carbon, with the substitution pool accounting for >50% of the total carbon. However, when substitution effects were not included, the no harvest and the longest harvest rotation cycle scenarios accumulated the most carbon. The study does assume that essentially all of the harvested wood is put to use, with about 50% allocated as long-lived lumber products with a life span of 80 years and the remaining 50% used for the production of bioenergy either as short-lived products or hog fuel, exercising fuel displacement with essentially no waste of harvested wood after logging. While the wood products industry has high rates of mill residual utilization, assuming that 100% of residual material is utilized for bioenergy is very optimistic.

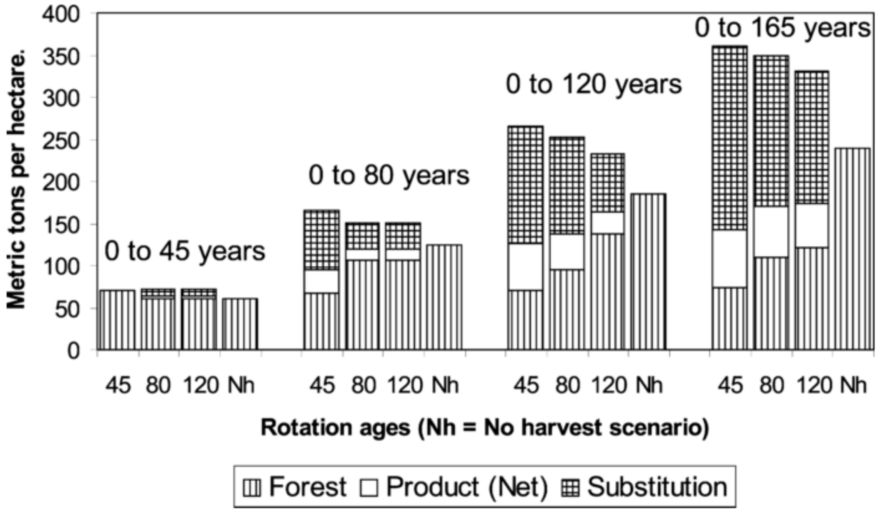

Figure 1. Average annual carbon in forest, product, and concrete substitution pools for different rotations and specified intervals [37].

Using a range of modelled management and biomass utilization scenarios, Gustavsson et al. [19] came to similar conclusions as Perez-Garcia et al. [36], finding the most climatically beneficial scenario for reduced radiative forcing to be a strategy aimed at high forest production, a high residue recovery rate, and high efficiency utilization of harvested biomass. Oliver et al. [39] agrees with some of these conclusions, but suggests that harvesting at the culmination of mean annual increment, closer to 80 years in coastal Douglas fir, provides the greatest carbon reduction benefit when displacement and substitution are included. More in line with Oliver et al.'s conclusions, Franklin et al. [23] found that, when including in-use wood product pools, disposal pools, product substitution, and in-forest carbon pools, longer rotations (+70 years) store more carbon per land area than shorter rotations, despite the benefits of substitution. These conclusions generally align with the studies labelled "conserve" or "moderate" in the summary table included as Table S1.

Again, substitution is a key variable in determining cumulative carbon benefits over time. Franklin et al. [23] discuss 6 key factors in determining the magnitude of substitution effects through time: (1) the amount of product-in-use created from the harvest, (2) the displacement factor, (3) percent of the harvest that will substitute for non-wood products like concrete or steel, (4) the cumulative nature of the substitution effects, (5) the length of time the substitution effect accumulates, and (6) the effect on the average lifespan of buildings if wood is substituted for fossil fuel intensive materials. Others generally recognize many, if not all, of these factors as important variables.

The displacement factor considered in analyzing substitution varies depending on the building system and the embedded GHG emission factor within displaced materials [23,25,40]. A meta-analysis of 21 different international engineering studies found the average displacement factor value to be 2.1, meaning that for each ton of wood products substituted for non-wood products, there is an average GHG emission reduction of approximately 2.1 tons of carbon (tC) [40]. While widely used, this number is a global reference average and likely not accurate for any given place and time. Uniquely local and dynamic biological and socio-economic factors such as, silvicultural systems, tree species, form and age of trees, amount of wood degrade, mortality rates, market demand, economics of transporting to processing facilities, and supply quota agreements, greatly influence commercial wood products and thus any attempts to quantify substitution rates and life cycles [22].

Where proponents of longer rotations [14,23,27,39,41,42] vary from those of more intensive management [19,36], seems to be largely centered around the assumed percentage of harvested wood that will be used in substitution for more fossil fuel intensive materials, and the cumulative nature of these substitution effects over time. Franklin [23] models out carbon substitution effects and carbon flux for 70 years; two rotations at 35 years and a single rotation at 70, whereas Perez-Garcia [36] accumulate substitution effects out to 165 years. Franklin et al. [23] purposefully model a shorter time span than Perez-Garcia et al. [36] thus limiting the accumulation of the substitution pool. They suggest that as technology, wood use, and energy sources evolve into the future, so will the displacement factor associated with substitution, most likely declining. Perez-Garcia et al. [36] also approximate a nearly 100% substitution rate (50% allocated as long-lived lumber products with a lifespan of 80 years and the remaining 50% used in the production of bioenergy), whereas Franklin et al. [23] model substitution rates of 50% and 75%. These differences in assumptions regarding percentage of product counted toward substitution and how the effects of substitution are modeled for subsequent periods seems to be the crux of the difference in their approaches and subsequent disagreement in management tactics to optimize carbon mitigation benefits.

While this discussion focused mostly on two studies the authors found to be representative of different perspectives, modeling approaches and subsequent management recommendations offered in various LCA style studies in the region, we categorize 14 studies as either: (1) conserve-forest management approach associated with relatively longer harvest cycle (+80 years), if any, (2) moderate forest management approach associated with extended harvest cycles (60–80 years) and increased retention strategies, and (3) intensive-forest management approach associated with relatively shorter harvest cycles (35–45 years). Results are presented in tabular format in the Table S1.

It is important to note that the concept of substitution also makes a range of assumptions around market demand and human decisions, assuming that in lieu of wood, similar to identical products and buildings will be constructed using alternative materials. These assumptions have led some experts to label substitution as a 'theoretical' carbon pool whose benefits have been overestimated by perhaps an order of magnitude [42].

2.4. End of Life

End-of-life assumptions about wood products and the fate of their carbon is another important consideration in LCA studies. Although including landfill carbon stores could increase overall carbon storage accounting, it is sometimes excluded in order to take a conservative approach. Skog [37] states that in 2005, about 2/3 of wood and 1/3 of paper not in use were discarded to landfills over other disposal scenarios in the U.S. The longer a product remains in the landfill, the more its original carbon content is preserved or "carried over." Harmon [33] found that about 14% of the carbon originally stored in a tree will remain in the disposal pool of solid wood products 200 years after entering an Oregon landfill.

One key area of uncertainty and variation pertaining to landfill stores is methane emissions and recapture. Methane has 21 times the global warming potential of CO_2 and can negate a significant portion of emission reductions from carbon stored in landfills [25]. Skog [37] found that in 2005, approximately half of total U.S. landfill methane emissions (=2 Tg C) could be attributed to decaying wood and paper. After complete decay of wood and paper, methane and CO_2 emissions can negate 55% of the landfill carbon stored as wood and 135% stored as paper, assuming a 50% methane capture rate [25]. However, future improvements in landfill methane emissions capture and reduction technologies have the potential to significantly increase landfill stores.

2.5. Carbon Carry-Over

The concept of carbon 'carry-over' refers to a ratio that relates pre-harvest, on-site carbon stores to post-harvest, on-site + off-site carbon stores, integrating measures of harvest and processing efficiency. Carbon carry-over refers to the amount of carbon converted to, and maintained within, wood products from a harvested tree (see for example Figure 2), as well as accounting for logging and mill residuals, and is crucial for establishing decay rates and stock flows for each pool.

The actual carry-over ratio for a given harvest depends on a number of site-specific factors such as logging and mill processes efficiency, and the nature of the product. Thus, the carry-over for any individual product originating from any given harvest will vary. However, various studies have investigated regional averages [22,37,43]. Following on the work of Milota et al. [43] and others, Franklin et al. [23] divided a harvested tree's biomass from a typical Douglas fir plantation into categories (Figure 2). They estimate that 27% of the standing live-tree is converted into structural lumber, 15% is made into chips for pulp and other products, 10% is mill residuals, 8% is used as boiler fuel, and 40% of a given tree's biomass is non-merchantable logging residuals, left to decompose or burned in piles.

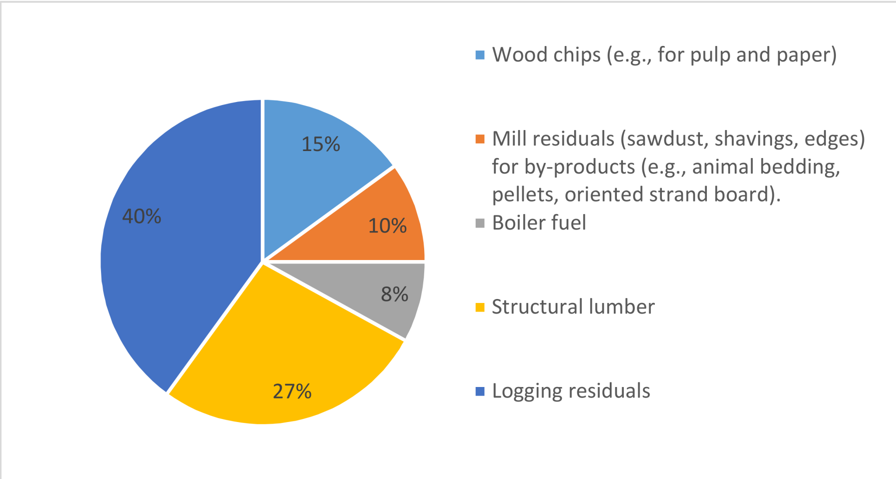

Figure 2. Tree biomass (Douglas fir) division upon harvest [23].

Carbon carry-over is a dynamic attribute of the forest carbon lifecycle changing over time as harvest systems and wood utilization evolves. Carbon carry-over calculations may vary drastically based on the criteria and assumptions used. While generally, there may be more scientific consensus and datasets available to quantify pre-harvest carbon stores, post-harvest carbon stores may be open to more variation depending on the harvest and processing carbon losses considered. Pre-harvest stores determine the carbon "starting point" or maximum carbon store that could be available in a final, processed wood product before accounting for decay, product life span, allocation or other carbon loss factors. Some calculations only consider post-harvest carbon stores of solid wood in use, while other calculations may consider solid wood in use and disposed, thus expanding the total available carbon store pool. In calculations that include solid wood, the disposal pool, disposal route (landfill vs. incineration for example), and decay rate assumptions affect results.

Recent studies from Harmon [33], Franklin et al. [23], and Talberth [27] suggest an average carbon carry-over value for Oregon forests ranging from 22% to 27%. Harmon used a process-based model to estimate the accumulation of solid wood products, those in use and disposed, and found that between 2003 and 2013, 23% of the carbon harvested on private lands resulted in a net increase in product stores. Ingerson [35] found a national average of 18% of original live tree volume available as a carbon store in wood products after accounting for volumes lost during harvest and processing. Further, Ingerson [35] suggests that estimates of wood product carbon stores still in use after 100 years can be as low as 0%–4.6% of the original live tree carbon store.

A European based study examining the comparative carbon benefits of unmanaged versus production forests found cumulative net carbon emissions and recovery times were especially sensitive to assumptions regarding reference fossil fuel, material alternatives to wood, forest growth rates, and energy conversion efficiencies used in substitution values [44]. Several LCA studies of forest bioenergy have concluded that the carbon recovery time can vary in length depending on forest type, ecoregion, management practices, and feedstock type (e.g., stem wood versus underutilized residuals) [34,45]. Many find that using underutilized biomass like logging or mill residuals (to the extent these are available and unused) can produce net positive GHG reductions in a relatively short timeframe [46].

2.6. *Leakage*

Leakage is an important concept in carbon accounting and refers to the phenomena of impacts or emissions merely being transferred from one location to another rather than being avoided or alleviated all together. Simply put, constraining timber supply in one location may shift demand to other locations. Ideally, an acknowledgment and understanding of the larger impacts of forest management decisions and their effect on leakage is incorporated into land management planning and policies, but this is rarely done in practice [47]. Moreover, given that leakage is a macroeconomic phenomenon, it is rarely incorporated into LCAs of harvested wood products. None of the 14 studies cited within the Table S1, nor others discussed in this section, directly incorporate leakage into accounting frameworks, while leakage is often acknowledged by the authors of these studies to be a real phenomenon. Strategies for addressing leakage vary, but generally amount to discounting the volume of additional carbon stored in forest carbon pools to account for some increase in carbon loss elsewhere, as is typically done in forest carbon offset projects [48].

The potential for leakage has been a central criticism of extending harvest rotations or more restrictive forest practice laws in the PNW. Law et al. [14] found that extending rotations in Western Oregon would yield greater in-forest carbon stores and potentially larger timber volumes in the long-run with a potential short-term decline in regional timber supply. They acknowledge that leakage could counter carbon gains, but believed that "because harvest on federal lands was reduced significantly since 1992 (NW Forest Plan), leakage has probably already occurred" [14].

Leakage did occur following the significant reduction in timber supply from federal lands in the PNW, however, as private forests in the region were already near max output, the impacts on harvesting levels appear to be minor (see Figure 3). At the same time, ongoing expansion and maturation of pine plantations in the Southeastern U.S. offered a significant source of softwood timber to supply newly unmet demand [49]. Analysis of leakage at a regional-scale reveals greater overall carbon gains (i.e., positive leakage) then had the shift in production not occurred [50]. Murray et al. [51] conclude that the net effect of a market shift from harvesting of old forests in the PNW to increased removals in the southeast U.S. and Canada resulted in a lower carbon loss to the atmosphere per harvested volume, in part due to continued expansion of fast grown pine plantations in the southeast U.S.

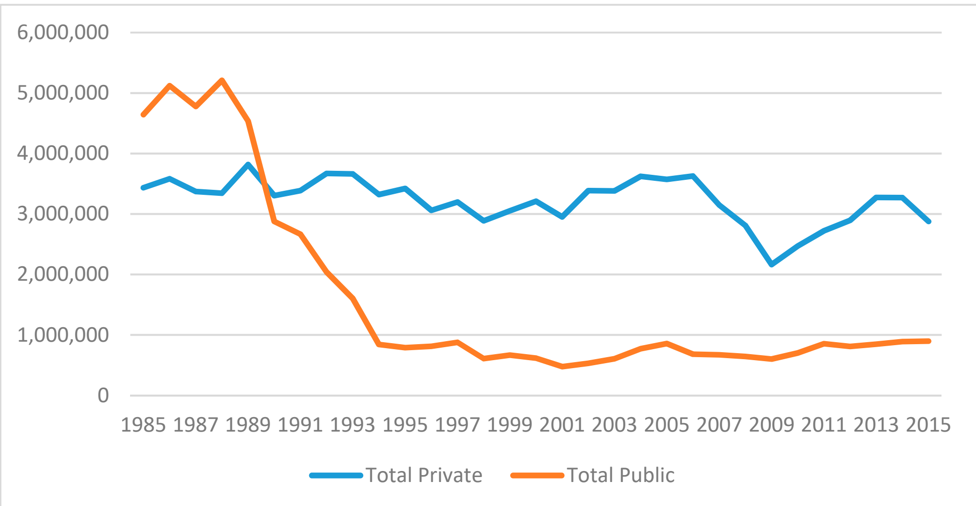

Figure 3. Timber Harvest in Oregon by Thousand Board Feet (1985–2015). Source: [52].

3. Climate Change Impacts and Uncertainty in Forest Management

A critical and difficult to model factor in considering potential trade-offs in forest management strategies is, ironically, climate change itself. Most of the PNW has warmed by 2 degrees (°F) with temperatures projected to increase by an average of 3–7 °F by the 2050s, and 5–11 °F by the 2080s if global emissions continue unabated [53]. If emissions level off by mid-century, warming could be limited to 2–5 °F by the 2050s and 2–7 °F by the 2080s [53]. Under either scenario, shifting precipitation patterns, drier summers, and reduced snow-pack will likely result in increasingly water-limited forest systems, with resultant droughts and wildfires occurring over larger areas.

Water stress can lead to reduced growth rates, increased tree mortality from insects and disease, and increased wildfire risk [5,54]. Globally, the negative carbon effects of increasing disturbance and mortality may be offset somewhat by enhanced productivity due to CO_2 and nitrogen fertilization and longer growing seasons [2], however, trees and other plant life can only benefit from increased nutrients in the presence of adequate soil moisture [55]. Significant uncertainty in projected changes to regional precipitation regimes make it difficult to predict forest response to increased CO_2 and nitrogen fertilization. What is becoming clearer is that warming temperatures in the PNW are likely already increasing mortality rates in critical, high carbon forests [5,50].

While wildfires have been a relatively small contributor to emissions in recent years [14], wildfire occurrence and severity are projected to increase. Models show the effects of climate change doubling the average annual burned area as well as increasing average fire intensity throughout the region [53]. Increasing fire frequency and severity, in combination with increased temperatures, are expected to result in profound shifts in the geographic extent of certain ecosystems and the carbon they contain [5,54,56].

These projections illuminate the difficult task for forestry; planning for an uncertain future with no historical analogue [57]. Shifts in forest management to attain higher forest carbon stocks must be balanced with the risk of increasing mortality rates associated with climate change. This highlights the need for an adaptive management approach that acknowledges uncertainties and changing conditions and seeks to be iterative, constantly responding to new feedbacks. For instance, longer rotation forestry likely needs the accompaniment of active monitoring and management actions, such as, "sanitation harvests" of dead and/or diseased trees. Simply extending rotations, without active management, may expose landowners to higher risk from disease, insect, and fire related mortality. On the other hand, older, more diverse stands can be more resistant to drought and disturbance than younger plantation style forests that lack species diversity [23,57].

4. Climate Smart Forestry as an Adaptive Management Approach

As a concept, 'climate smart forestry' involves practices that meet a triple bottom line criteria of providing social, ecological and economic gains [58]. In climate smart forestry, management practices are emphasized that mitigate GHG emissions while enhancing a system's ability to adapt to the effects of climate change, sometimes referred to as joint mitigation and adaptation (JMA) strategies. This approach does not mean managing for no-harvests, nor does it necessarily mean minimizing or maximizing harvests or extending rotations. Rather, a climate smart paradigm strives to be holistic in understanding the effects of land management decisions and policy on social and economic factors at both the local and global scale.

Recent analyses have sought to identify what wood-processing infrastructure and market components are needed to facilitate a transition to climate smart forestry across the moist and dry forests of the PNW [59–62]. There is a need for spatial analyses that differentiate forest management and product pathways capable of increasing carbon carryover ratios from on-site to off-site carbon pools while enhancing the adaptive and carbon storage capacity of the region's forests. Resultant data can inform recommendations for public and private investments in wood processing infrastructure that consider both socio-economic factors (e.g., availability of wood supply and skilled labor, transportation costs) and ecological variables (e.g., forest productivity, projected volumes of restoration wood).

5. Takeaways for the Moist Forests of the Pacific Northwest

5.1. Managing Trade-Offs between Extended Rotations and Short-Term Wood Supply

Historically, carbon storage has not been a consideration for forest managers in the PNW. As a result, private forests in Oregon's coast range are currently storing approximately one third of their ecological potential [12,13,50]. Between 2001 and 2010, private industrial forests in the Oregon Coast Range averaged 113 mtCO_2e/acre across 2.2 million acres, while unreserved U.S. Forest Service lands averaged 278 mtCO_2e/acre in the same ecoregion [50]. Carbon levels on private lands reflect common forestry practices focused largely on even-aged monocultures or semi-natural planted forests grown on ~40-year rotations.

If optimizing sustained yield of timber volume were the objective, forests in the PNW Coast Range would likely be managed on longer rotations producing a net-increase in both above ground carbon stocks and timber volume [14,63]. Extending the average rotation on private forestland in western Oregon is consistent with the findings of Oliver et al. [39], that "harvesting sustainably at an optimum stand age will sequester more carbon in the combined products, wood energy, and forest than harvesting sustainably at other ages", Curtis [64] produced growth and yield curves for managed Douglas Fir in the PNW Coast Range and also studied culmination of mean annual increment (CMAI) for these forests [65]. Max mean annual increment is estimated to range from ~90 to 117 years in high to low site classes [65,66], rather than the financially optimal rotation of ~40 years currently common in the region [63]. Figure 4 illustrates the effects of maximising short-term finacnial returns on forest age with subsequent impacts on on-site carbon storage and accumulation.

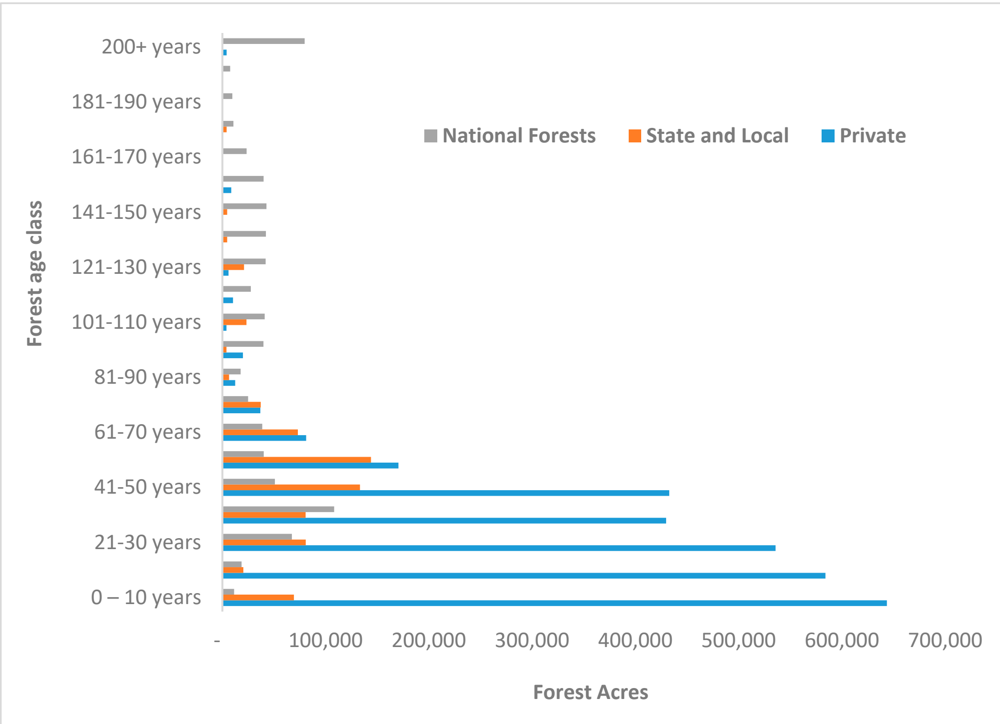

Figure 4. Age class distribution in the Oregon Coast Range as of 2016 arranged by ownership class. Source: United States Forest Service (USFS) Forest Inventory and Analysis, accessed from the Evalidator database July 2018.

The imbalance of age classes on private lands is a persistent problem with many negative ecologcial consequences that have long been recognized and discussed [67,68]. Increasing age class diversity and average age in private forestlands across the PNW Coast Range could have profoundly positive carbon impacts.

A topic of some disagreement within the literature is the natural decline in carbon sequestration rates as forests age. Analyzing regional USFS Forest Inventory and Analysis (FIA) data, researchers have come to different conclusions regarding carbon sequestration rates in moist PNW forests, and consequently perspectives on optimal strategies for forest carbon management. Some have found no marked decline in net primary productivity in forests older than 200 years in many ecoregions of Oregon and Northern California [69]. Others suggest forest growth rates peak in federal forests in western Washington at ~100 years of age, with declining growth rates and carbon accumulation thereafter [25]. Focusing exclusively on even-aged stands, Malmsheimer et al. [21] noted that sequestration rates peak in the first 100–150 years in most stands as they subsequently begin experiencing increased mortality rates.

An analysis of Pacific Northwest region-wide FIA data covering the majority of forest types and ownerships found that by year 127 (±35 years) forests had sequestered 75% of their potential carbon stores [17]. Similarly, Hudiberg et al. [69] documents positive primary productivity at 80–125 years across a range of forest types in Northern California and Western Oregon. Sequestration and net carbon storage can continue for several hundred years in aging forests, particularly in the Klamath-Siskiyou, Coast Range, and West Cascade ecoregions [69,70].

Overall, when both above and belowground carbon stocks are considered, old-growth forests can be found to store an average of 50 percent more carbon than managed forests on some sites [22,71]. Likewise, recent analyses underscore that net primary production continues well beyond standard timber rotation lengths, and that net accumulation continues for up to 400 years or longer [17,69,70].

While there a few exceptions, our review of the literature found general agreement concerning an alignment of peak primary productivity and CMAI. A key IFM strategy for the region is thus extending rotations to the CMAI. Griscom et al. [7] conclude that widespread implementation of IFM has the ability to both increase carbon stores and meet global wood demand. Likewise, Harmon and Marks [41] conclude that IFM in the form of partial-cutting systems (i.e., alternative silviculture to standard rotation even-aged management), and/or longer rotations, offers the best outcomes in terms of balancing carbon stores against production of forest products.

Law et al. [14] estimate that extending rotations from 45 to 80 years could decrease harvested forest carbon on private lands by 2 TgC/year (7.32 million mtCO_2e/year). If implemented simultaneously on all private lands in Oregon, this would represent a 26% decrease in short-run harvested carbon compared to 2001 and 2015 [50]. While such harvest rotation extensions would likely lead to short-term leakage, net volumes of harvested timber could increase in the long term. This finding aligns with that of Franklin et al. [23] who found that harvest intervals of 70 years to be a more favorable carbon storage strategy in Pacific Northwest moist forests, when factoring in wood product stores, disposal stores, and product substitution.

Using Curtis' growth chart and a reference ratio of 15.335 C lbs/ft^3 (=0.026 mtCO_2e/ft^3) for coastal Douglas fir [24], we find extending rotations on class II growing sites in the Oregon coast range from 40 to 90 years could gross up to 216 mtCO_2e/acre of carbon gain over the interim 50 years. Moving the 862,000 acres of private coastal timber land in Oregon currently between the ages of 31–50 years to 81–90 years could result in an gross gain of 202 million mtCO_2e over the next 40 to 50 years. These numbers are an estimate of gross carbon gain as they do not account for mortality or any management actions and merely serve to demonstrate the substantial carbon gains available by extending harvest rotations to more closely resemble CMAI. More in depth study and analysis will be needed to outline economically viable forest management strategies and silviculture regimes that increase carbon stores across private forests.

While our review found multiple lines of evidence for extending rotations toward the CMAI as a climate optimal strategy, we identified a lack of studies evaluating the effects of a gradual transition to longer rotations and shifts in milling infrastructure and forest markets, with a few notable exceptions. Montgomery et al. [59] and Latta and Montgomery [60] examined the effects of timber prices on demand and supply response for large diameter logs grown on longer rotations.

Diaz et al. [63] analyzed average carbon storage in the forest and wood products; cumulative timber output; and discounted cash flow for four alternative management scenarios for Douglas-fir forests on 64 parcels across western Oregon and Washington. They found higher carbon storage and timber yields in extended rotations compared to business as usual, with modest wood premiums and/or carbon incentive payments needed to close the financial gap between extended rotations and business-as-usual.

5.2. Land Use: Keeping Forests as Forests

While this paper focuses mostly on forest management and wood products, land use and its effects on regional carbon stocks is integral to any efforts to optimize carbon management. The co-benefits of keeping forests as forests are vast and the need is significant. About 6% (~1.4 million acres) of all forests in Washington were converted to other uses between 1970 and 2008 [72]. Oregon, frequently held up as a paragon of land use policy, lost an average of nearly 51,000 acres each year between 2000 and 2014 [73].

In both states, the majority of loss was due to urban development. When forests are lost to development, emissions from total harvests, the ensuing loss of future sequestration capacity, and the addition of secondary emissions from new buildings replacing forests, all need to be considered. These secondary emissions are not captured in estimates of forest carbon flux, meaning that the effects of land use change are significantly larger when the carbon footprint of land uses replacing forests are considered. A recent study of FIA data across Oregon and Washington found that forestland conversion occurring between the 1990s and early 2000s negated 25% of the additional forest carbon that accumulated in these states over the same period [13]. The rate of conversion is likely to continue or increase as the Pacific Norwest is experiencing a surge in population growth [74]. As both Oregon and Washington attempt to curtail their emissions, a harder look at development pressure on forests and agricultural lands is warranted.

5.3. Considering the Role of Forests in Pacific Northwest Climate Policy

Both Oregon and Washington have set ambitious GHG emission reduction targets. In 2007, Oregon set statewide goals of reducing emissions to 10 percent below 1990 levels by 2020 and 75 percent below 1990 levels by 2050. In their 2017 biennial report to the legislature, the Oregon Global Warming Commission revealed an increase in state emissions largely due to the transportation sector. The report forecasts that Oregon will miss its 2020 target, and will likely exceed 2035 and 2050 goals. This, despite an updated Renewable Portfolio Standard and a commitment to phase-out of coal-produced electricity by 2030 [75].

To help guide the state toward meeting their emission reduction goals, in 2010, the Oregon Global Warming Commission adopted The Roadmap to 2020, which set out broad objectives and specific tasks for managing the carbon contained in Oregon's forests. One goal was, "no net loss of Oregon forested lands and a net gain in carbon storage in an amount to be determined" between 2010 and 2150. The Roadmap also set out general strategies for dry forests east of the Cascade Mountains versus moist west of the Cascades. Based on improved understanding of the carbon storage capacity of the state's forests, the 2017 Global Warming Commission Report explained that, "The Roadmap sees 'Eastside forests ... managed primarily for ecosystem restoration, safety and climate adaptation with a minimum of incurred carbon (loss). West-side forests (are) managed ... to increase carbon storage ... private forestlands (are) managed primarily for production of timber and wood products ... ' with carbon stores remaining stable or increasing". The 2017 Warming Commission Report did not suggest specific carbon goals for Oregon forests as were called for in their 2010 report, but did lay out next steps to better understanding what the potential role of forests might be in reducing state level emissions: Establish a carbon inventory for Oregon forests; Pursue reforestation/afforestation; Invest in key research actions to identify impacts of climate change, adaptation tools, and benefits of durable products; and Advance energy and forest policies supporting biomass facilities.

The first step of inventorying Oregon's forest carbon was accomplished in partnership with the USDA Forest Service Pacific Northwest Research Station using state-specific FIA data. The data reveals that carbon stocks on privately owned forests in the PNW Coast Range, whether industrial or non, are approximately roughly a third of ecological potential.

From 2016 to 2018, a number of forest carbon inventories were completed by the Pinchot Institute for Conservation on non-industrial forestland in western Oregon and Washington using the improved forest management protocols of the California compliance offset market [48]. Inventory results (Figures 5–8) indicate that many private, non-industrial forests in the region are in the process of recovering their carbon stocks and are close to regional average stocking levels of 121–141 $mtCO_2e$/acre—again, approximately a third of the ecological potential of older forests. Other properties inventoried had significantly higher carbon stocks, with some having more than twice the regional average $mtCO_2e$ per-acre (see Figures 5–8 for comparison).

Figure 5. A mature Western Red cedar stand in the Oregon Coast range. The stand averaged 280 $mtCO_2e$/acre.

Figure 6. A mixed age, mixed species stand dominated by Douglas Fir in the Oregon Coastal Range. This stand averaged 170 $mtCO_2e$/acre.

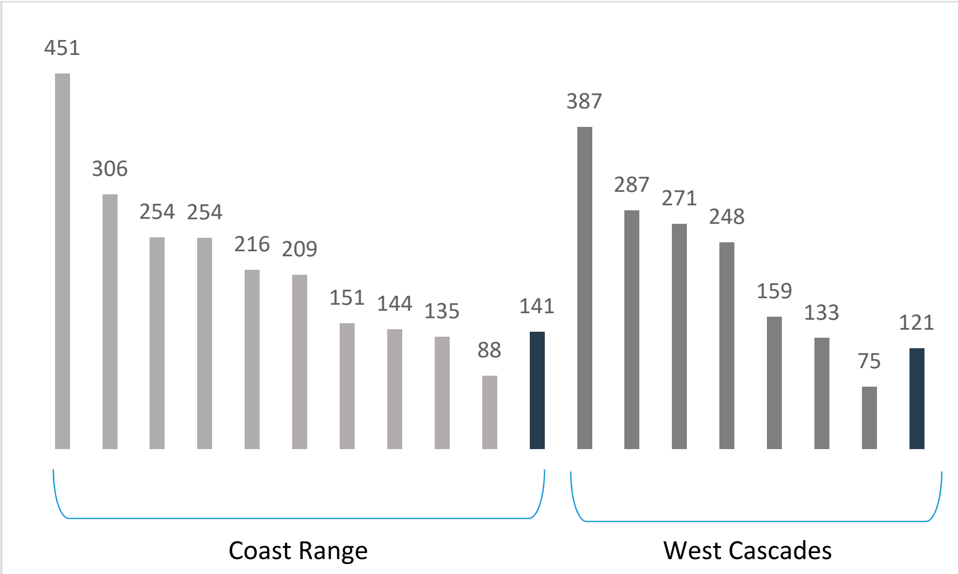

Figure 7. mtCO_2e/acre measured in 2017 on 17 private non-industrial forestland in Oregon compared to California Air Resource Board regional baselines (in black).

Figure 8. A 35–40 year old, densely stocked Douglas Fir stand in the Western Cascades. This stand stores an average of 120 mtCO_2e/acre.

Policy makers seeking comprehensive solutions that optimize climate outcomes are confronted with a need to devise strategies that incentivize both the conservation of high carbon stock forests, and to address forests in the early stages of recovering their carbon stocks. All this while continuing to manage timber supply. Conserving and sustainably managing older non-industrial forests using a partial cutting systems is one option. Supporting market and infrastructure development for larger diameter logs, as well as ensuring carbon markets are open to smaller acreages, are complementary strategies for supporting this type of forestry [59,60].

A strategy for moderating potential timber supply deficits that might arise from extending rotations could be targeting policies to segments of the landownership-base best suited for such management. A few industrial forestry companies, mostly family owned businesses, currently grow timber on longer rotations. However, it remains highly unlikely that large institutional investment forestland ownerships will voluntarily shift practices significantly from those that maximize financial returns. On the other hand, non-industrial forest owners own and manage their lands for multiple ownership objectives with financial outcomes being just one [76,77]. Forest management to increase carbon storage and payments for forest carbon sequestration have potential, with surveys indicating up to half of non-industrial forest owners in the U.S. may be interested in carbon offset markets [78]. Yet, given the structure and barriers to entry in current carbon offset markets, participation has been extremely limited to date.

5.4. Forest Carbon Incentive Program

The need to quantify potential policy effects and maximize the cost-effectiveness of incentives has led some to conclude that the rigorous carbon accounting required for offset projects may not always be desirable or necessary. Through their review of the literature, Malmsheimer et al. [21], conclude that, "the measurement challenges and relatively high transaction costs inherent in forest carbon offset systems motivate consideration of other policies that can promote climate benefits from forests without requiring project-specific accounting". This sentiment was echoed by numerous agricultural and forest stakeholders during a 2018 conference on carbon pricing in Oregon [79].

Modelled on existing Farm Bill programs, forest carbon incentive programs have been proposed as a means to incentivize carbon storage in non-industrial forests [80,81]. The core of the concept is to: (1) assign emission reduction rates for certain practices (e.g., rotation extension, reduced impact logging, other JMA/IFM practices) based on the best-available science, modelling, and sound carbon accounting principles, (2) quantify emission reduction benefits not at the parcel level, as is done in carbon offset projects, but at the programmatic level, via periodic inspections by state forestry agencies and/or via remote sensing. While this approach would avoid many of the barriers and downfalls of offset markets, solicit broader participation and potentially sequester significant additional carbon on the landscape, less rigorous carbon accounting standards may also preclude states from counting such gains against emission reduction targets.

The inverse of an incentive-based approach to promote behavior change is regulation. On federal forests in the PNW, endangered species regulations have dramatically reduced commercial timber harvests since the early 1990s. As a consequence, most of the gains in carbon storage within the region's forests occurred on these lands as above ground stocks expanded. This illustrates the effect a change in policy can have on ecosystem services, including carbon storage [82]. On private lands, regulatory changes in forest practices that restrict the size of openings, require retaining more trees in clearcuts, and/or expanding riparian buffer widths, could all have a directly positive effects on carbon stocks.

6. Conclusions

Our review of forest carbon LCA and modelling studies from 2006 to 2018 classifies the various forest management regimes identified by these studies as providing optimal carbon management. These forest management approaches include: (1) conservation management or forest management associated with multiple values such as wildlife habitat and carbon sequestration, and generally associated with relatively longer harvest cycles (80+ years), if any; (2) moderate management or a forest management approach associated with extended harvest cycles (60–80 years) and increased retention strategies, and; (3) intensive management or forest management strategies associated with industrial timber production including harvest cycles of 35–45 years. We found that the selection of a preferred forest management approach as optimal for forest carbon management correlates with modeling assumptions and the inclusion or exclusion of LCA inputs.

In the studies examined, we identify key differences in assumptions about substitution benefits and their accrual over time, the carryover of carbon from in-forest pools to the wood product and disposal pools, and the length of wood product lifespans. These differences in assumptions, particularly differences in accounting for substitution, translate into varying results and subsequent disagreements about optimal forest carbon management tactics.

Our review found near consensus regarding net primary production in the moist forests of Western Oregon and Washington and the timber rotation length at which wood volume is optimized, i.e., the culmination of mean annual increment. Where proponents of longer rotations [14,23,41] vary from those of more intensive management [25,36] seems to be based largely on the assumed percentage of harvested wood that will be used in substitution for fossil fuel intensive materials and the cumulative nature of these substitution benefits over time.

While much of the literature on climate smart forestry emphasizes "win-win" management solutions, there will likely always be competing values in forest management. It is also likely that there will be competing science and recommendations for how best to achieve optimal climate mitigation and adaptation outcomes. Having a clear understanding of the trade-offs involved in any forest management regime, in terms of carbon storage (and the attendant social costs of emissions), economic output, and ecosystem services such as water and air quality, is vitally important. As the climate changes and demand for wood products shifts in the coming decades, policy makers and land managers will need to continually re-evaluate these tradeoffs and adjust practices based on the most recent scientific and economic data available.

However, based on current conditions and what is known about the temperate rainforests of the Oregon and Washington, some recommendations for optimal forest carbon management can be made. Strategies in this region involve a combination of preserving old forests where they exist and increasingly managing public forests toward these conditions. On private forests west of the Cascades, extending harvest rotations towards the CMAI, maximizing utilization of harvested biomass, focusing on production of durable and long-lived wood products, and altering harvest practices to retain more live trees on-site, all could result in significant net carbon gains. Complementary strategies for supporting a shift towards this type of management in the moist forest region may include investments in market and infrastructure development for larger diameter logs, as well as encouraging the development of carbon markets. There is a need for improved economic analysis of the effects of a gradual transition to longer rotations and corresponding shifts in milling infrastructure, log supply, and associated carbon impacts. In the dry forests of the PNW, climate optimal management may vary from these strategies, in some cases substantially.

As the impacts of climate change and the mechanisms driving it become better understood and more widely accepted, it seems likely that some form of carbon pricing is inevitable. Carbon emissions have real public impacts and costs and should be valued as such. In his now famous report, former lead economists for the World Bank, Sir Nicholas Stern, stated that climate change was a result of, "the greatest market failure the world has seen" [83]. As forests are a significant piece of the global carbon cycle, it also seems likely that carbon accounting and management will be an increasingly important facet of forest management. In the PNW, optimizing the emission reduction potential of forests may represent the single greatest potential opportunity for states to not only reduce in-boundary GHG emissions, but also to begin removing additional carbon from the atmosphere.

States will likely need a mixture of carbon pricing, incentives, regulation, and strategic market and infrastructure development in order to affect common forest management practices significantly enough to wield their forests as effective emission reduction strategies.

Recommended Strategies for Optimizing Climate Outcomes from Forest Management

- Develop targets for expanding forest carbon stocks, segmented by ecoregion and ownership. Emphasize storage in ecosystems with high ecological potential and lower risk of losing carbon through climate driven disturbance.
- Maintain the forestland base by employing 'No net loss of forests' or 'no net loss of forest carbon' policies.
- Maintain a mosaic of age classes across the forest landscape to balance robust growth rates, production of durable wood products, the conservation of old forests, and a gradual transition to older forest age-classes.

- Build wood product and carbon markets, and necessary wood product infrastructure, to move toward longer rotation forestry (50–90 years) in the moist forest region.
- Mitigate potential leakage through comprehensive policy design and careful implementation.
- Differentiate forest management and product pathways that increase the carbon carryover from on-site to off-site carbon pools. Such pathways should be encouraged and paired with long-lived building systems that displace GHG intensive products.
- Align economic incentives (tax breaks, loan guarantees, grants, etc.) to overcome barriers to realizing the most carbon beneficial forest management and wood product pathways.
- Focus on forest practices that mitigate GHG emissions while enhancing adaptive capacity.
- Increase retention at harvest (e.g., leaving wider riparian buffers, leaving groups of standing live and dead trees).
- Expand investments in forest resilience programs to minimize risk of high severity wildfire and reduce climate driven forest mortality, and associated carbon stock loss.
- Employ principles of adaptive governance in state forest practices acts to respond to climate change impacts and build forest carbon stores.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/9/10/618/s1, Table S1: Pinchot Institute Literature Review Analysis.

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