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Forests
Volume 9 - Issue 8 | August 2018

mdpi.com/journal/forests
ISSN 1999-4907

Ecotrust

forests

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Article

Tradeoffs in Timber, Carbon, and Cash Flow under Alternative Management Systems for Douglas-Fir in the Pacific Northwest

David D. Diaz [1,2,*], Sara Loreno [2], Gregory J. Ettl [1] and Brent Davies [2]

[1] School of Environmental and Forest Sciences, University of Washington, P.O. Box 352100, Seattle, WA 98195-2100, USA; ettl@uw.edu

[2] Ecotrust, 721 NW Ninth Ave, #200, Portland, OR 97209, USA; sloreno@ecotrust.org (S.L.); bdavies@ecotrust.org (B.D.)

* Correspondence: ddiaz@ecotrust.org; Tel.: +1-503-467-0821

Received: 29 June 2018; Accepted: 23 July 2018; Published: 25 July 2018

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Abstract: Forest management choices offer significant potential to mitigate global climate change and biodiversity loss. To illuminate tradeoffs relevant to policymakers, forest sector stakeholders, and consumers of forest products, we utilize three Key Performance Indicators—average carbon storage in the forest and wood products; cumulative timber output; and discounted cash flow—to compare four alternative management scenarios for Douglas-fir forests on 64 parcels across western Oregon and Washington. These scenarios are designed to meet one of two alternative management objectives: (i) maximize Net Present Value; or (ii) maximize sustained timber yield; according to one of two alternative sets of forest practice constraints: (i) compliance with minimum Oregon/Washington Forest Practices Act (FPA) rules; or (ii) two key requirements (increased green tree retention and wider riparian buffers) of Forest Stewardship Council (FSC) certification. Improved performance in terms of carbon storage for these alternatives generally also corresponded with reduced Net Present Value and timber yields. The gap between FSC and FPA performance indicators was wider in Oregon than Washington, which is primarily attributed to the higher level of stream protection required under Washington versus Oregon FPA rules. We observed consistently higher average carbon storage per cumulative timber output among FSC scenarios relative to business-as-usual, indicating FSC-certified wood carries an embedded carbon benefit. Our findings highlight options for targeted policies to incentivize management that increases carbon storage and minimizes disruptions in timber output, as well as for narrowing the financial gap (or opportunity cost) that would be involved in a transition away from contemporary common practice on industrial timberlands in the coastal Douglas-fir forests of the Pacific Northwest.

Keywords: forest carbon; timber production; cash flow; tradeoff analysis; Forest Stewardship Council (FSC); Pacific Northwest; Douglas-fir

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1. Introduction

1.1. The Productivity and Management of Coastal Douglas-Fir Forests

The coastal temperate forests of the Pacific Northwest are among the most productive ecosystems in the world [1]. Long-lived tree species such as Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western redcedar (*Thuja plicata* Don ex D. Don) and conducive growing conditions [2] interact to enable the accumulation of immense forest biomass over time [3]. Oregon and Washington are the two largest producers of softwood lumber in the USA, generating 16.5% and 11.8% of the country's softwood lumber supply in 2015 [4]. Roughly half of the productive forestland in the region, and nearly 90% of forest industry softwood timberland, is covered by Douglas-fir and western hemlock forest types [5]. Douglas-fir dominates timber volume and revenue production in the region and generally plays a foundational role in management, conservation, and policy decisions related to forests throughout the Pacific Northwest.

The management of Douglas-fir on industrial timberland in the Pacific Northwest west of the Cascade Range (see project area in Figure 1) is generally intensive, following an even-age silvicultural system including the selection of genetically superior planting stock, site preparation and the broadcast application of herbicides to limit shrub and broadleaf competition, and regeneration harvests (i.e., harvest to initiate a new stand) around financially optimal rotation ages of 40–50 years [5–7].

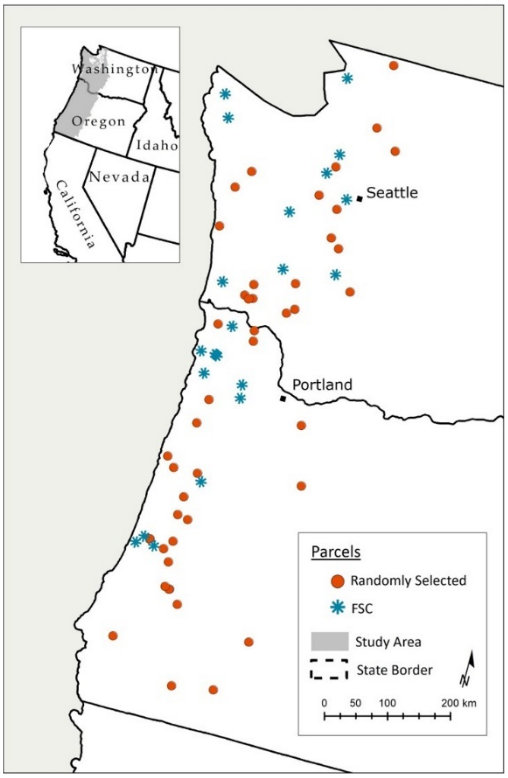

Figure 1. Study area. Actual FSC-certified parcels are distinguished from randomly selected parcels. All parcels are subject to the same suite of simulated management practices (both ~FSC and ~FPA scenarios). FPA: Forest Practices Act; FSC: Forest Stewardship Council.

The restructuring of industrial timberland ownership and vertical disintegration of major timber industry firms in the USA since the 1980s has given rise to an increasingly consolidated set of "financialized" investment entities such as Timberland Investment Management Organizations and Real Estate Investment Trusts [8–10]. These new timberland brokers and owners, backed primarily by institutional investors, have since replaced nearly all the largest industrial private forest companies in the USA [10]. This ownership shift has been described as the "financialization of landownership" and corresponds with an emphasis on silvicultural systems designed to maximize the return on investment from timberland [8,10].

The practice of managing Douglas-fir forests in the Pacific Northwest for maximum sustained yield of timber (i.e., rotations that maximize timber yield vs. those that maximize return on investment) has become progressively less common among private timberland owners [8]. For even-aged silvicultural systems, the divergence between the 'biological rotation age' at which maximum sustained yield would be achieved and younger 'financial rotation age' at which maximum return on investment would be achieved has been well-recognized in forestry since the nineteenth century, and has played a fundamental role in forest economics ever since [11].

A variety of long-term field trials and simulation studies have demonstrated an opportunity for long-term timber supply to be increased by the extension of rotation ages closer to the culmination of Mean Annual Increment (MAI) of timber volume growth, and that the integration of commercial thinning may extend the culmination of MAI further into substantially older ages than current common practice [11–16]. The extension of rotation ages is also well-established as a means to increase average carbon storage in the forest system and is a common component in forest carbon policies and research [6,17–22]. Previous work investigating the potential for carbon sequestration incentives to support the extension of rotation ages have specifically identified the coastal forests of the Pacific Northwest possessing unrivaled sequestration potential under a variety of carbon accounting approaches [17].

1.2. Policy Interest in Forest Sector Engagement in Climate Change Mitigation and Adaptation

In recent years, climate policy proposals in both Oregon and Washington have considered forests for potential involvement in climate change mitigation as well as for investments of climate program funds for adaptation. Although no economy-wide regulations of greenhouse gas emissions have yet been implemented, State-level policy proposals based on a carbon tax or fee, cap-and-trade, or variations such as "cap-and-invest" or "cap-and-dividend" have become an almost-yearly occurrence and are currently active in both Oregon and Washington via the State legislature and through citizens' ballot initiatives. The role of forests within these programs is especially relevant to local policymakers and forest sector stakeholders due to the historical natural resource dependence of many rural communities in the Pacific Northwest and the growing awareness of climate impacts on forests and communities in the region.

In this study, we focus primarily on the potential for forest management to contribute to the mitigation side of this policy discussion because we anticipate incentive programs and potential regulatory approaches dealing with the impacts of alternative forest management approaches on carbon balance. The exceptional productivity and biomass carrying capacity of coastal forests in the Pacific Northwest justifies the attention paid to them, both in terms of private and public capital investments in timberland management, as well as consideration of the climate change mitigation potential these forests may offer.

1.3. Interest in the Carbon Footprint of Wood, and the Central Role Certification Has Come to Play

A growing emphasis on green building and reducing environmental impacts in architecture and engineering fields has led to a proliferation of Environmental Product Declarations and a corresponding interest in wood as preferable building material relative to more energy- and carbon-intensive alternatives [23,24]. Our original motivation for this work evolved from an analysis of ecosystem service impacts involved in the construction and maintenance of The Bullitt Center, a six-story office building in Seattle, Washington, USA designed to meet the standards developed by the International Living Future Institute: The Living Building Challenge [25]. As part of this analysis, we were tasked to quantify the embedded carbon storage impact involved with the procurement of wood certified according to the Forest Stewardship Council (FSC) program. We evaluated the "upstream" carbon implications of forest management as a distinct process from the "downstream" design decisions regarding the use of wood or other materials in the construction of the building.

Programs that certify the sustainable management of forests have grown to assume a fundamental role as independent gatekeepers for emerging programs focused on reducing the environmental impacts humans produce. For example, the Living Building Challenge requires all wood used in projects to be FSC certified, from salvaged sources, or intentionally harvested from onsite. A similar preference existed for FSC-certified wood in the Leadership in Energy and Environmental Design (LEED) green building certification for many years. Third-party certification has also become a virtually universal requirement for all major forest carbon offset crediting programs now in operation in the USA and abroad, with an estimated 99.7% of carbon credits transacted globally involving the use of third-party certification [26]. The most widely subscribed forest carbon program in the USA is operated under the cap-and-trade program maintained by the State of California's Air Resources Board, which requires forest projects to demonstrate an independent certification of sustainable forest management in addition to the carbon offset verification in order to be eligible for carbon crediting.

Despite the preference for FSC in green building programs, very few examples exist of research quantifying the impacts that the additional constraints on forest practices required to achieve FSC certification may have. The most common approach to this type of analysis has focused exclusively on traditional forestry indicators such as timber output, forest sector employment in forest products processing, or financial performance of individual ownerships [27–30], ignoring the broader set of values, including ecological and social impacts, that form the basis of FSC Principles and Criteria for certification [31]. The integrated consideration of environmental impacts corresponding with FSC certification remains relatively sparsely covered in the peer-reviewed literature [20]. In this study, we explore these impacts and the potential for FSC certification to function as a surrogate for more elaborate carbon offset crediting mechanisms.

1.4. Research Objectives and Working Hypotheses

Our primary objective in this study is to quantify the impacts that selected silvicultural practices associated with FSC-certification have compared to business-as-usual forest management approaches. We build on earlier work by integrating both environmental and economic indicators that are fundamental concerns in ongoing discussions of forest carbon and climate policy. We apply three Key Performance Indicators (KPIs)—carbon storage, timber output, and discounted cash flow—to illustrate the potential for new policies such as forest carbon incentives to reduce financial barriers to the broader adoption of forest practices that increase climate change mitigation and a host of other ecosystem services.

In general, we expect silvicultural systems which employ longer rotations (timed to the culmination of Mean Annual Increment of merchantable timber volume) to carry and yield larger timber volumes and store more carbon over time than the more financially attractive shorter rotations. While greater timber output and carbon storage through extended rotations may seem like a clear win-win from a policy perspective, we expect gains in carbon storage and sustained timber yield to come at the expense of a non-trivial financial gap (or opportunity cost). This financial gap is likely to present a substantial barrier to the adoption of new forest practices by public and private landowners that could be engaged through programs focused on sequestering more carbon and/or generating more timber [32].

We also expect forest practices that retain more trees during regeneration harvests and which reduce or exclude intensive management around streams to translate into higher forest carbon storage over time. Forest certification programs that impose these types of constraints on harvest practices, such as the FSC-US Standard in the Pacific Northwest, are therefore likely to translate into additional carbon storage in the forest with a corresponding reduction in timber yield and Net Present Value.

2. Materials and Methods

2.1. Initial Forest Conditions

We assess the impact of alternative silvicultural practices using a range of forest conditions across landscapes where intensive Douglas-fir management is commonly practiced in the Pacific Northwest. A total of 64 parcels (covering 44,250 acres) were selected across western Oregon and Washington with the intent of covering a spectrum from small-to-large parcel size, as well as from sparse-to-dense coverage of riparian areas. Twenty-two of these parcels (covering 10,319 hectares/25,500 acres) have been FSC-certified (Figure 1). We selected the remaining 42 parcels (covering 7515 hectares/18,570 acres) from privately owned forest parcels larger than 40.5 hectares (100 acres) within the study region. These parcels were selected to offer a diverse set of parcel sizes and extent of riparian cover and are intended to communicate the range of variability that might be expected through the type of management scenarios we consider in this study if they were applied more broadly across the region.

Because ground-based inventory data were not available across all parcels to delineate stands or provide starting conditions, we utilized remotely sensed data to estimate initial forest composition. We delineated each parcel using a 2.02 hectare (5 acre) hexagonal grid to approximate management units, which are hereafter referred to as stands (Figure 2). Forest inventory data were imputed to each stand from the Landscape Ecology, Modeling, Mapping & Analysis group's Gradient Nearest Neighbor (GNN) database [33–35]. The GNN database provides a crosswalk between a raster image with 30 × 30 m resolution to forest inventory plots for each pixel. We summarized pixel-level inventory estimates up to the scale of the hexagonal stand using the majority forest type across pixels within each hexagon and selected the most commonly identified inventory plot of that forest type within the hexagon to represent that stand (i.e., a single forest inventory plot of the majority forest type to represent each stand).

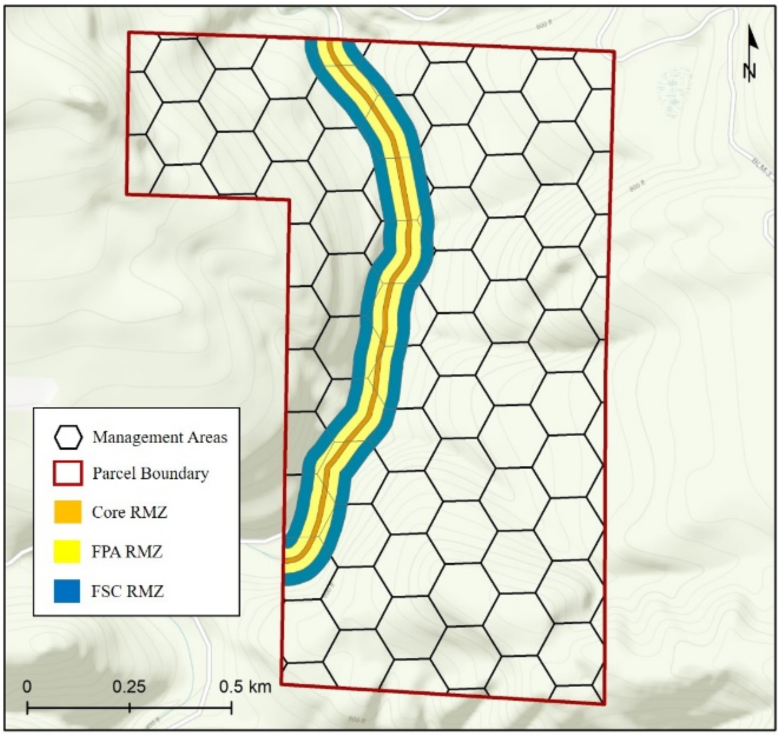

Figure 2. Each parcel is sub-divided into 2.02 hectare (5 acre) 'stands', which are then intersected with Riparian Management Zones (RMZs) to form distinct management units that are simulated individually. The parcel above shows the core and non-core RMZ areas delineated following FSC rules.

We imputed topographical attributes including elevation, aspect, and slope to each stand based on a Digital Elevation Model. Douglas-fir 50-year Site Index was estimated at the stand level based on maps produced by Latta et al. [36]. These Site Index predictions of Latta et al. were based on climatic drivers and vary relatively smoothly across the landscape; they are therefore unlikely to accurately reflect changes in site productivity following topographic or edaphic changes at small spatial scales (e.g., along streams or in rocky outcrops). Several measures illustrating the correspondence between the imputed attributes of the parcels selected for modeling and the landscape from which they were sampled are shown in Figure 3. Both the randomly selected and actual FSC-certified parcels are generally representative of the landscape across which they occur. The starting inventory conditions for randomly selected and FSC-certified parcels in terms of stand age, basal area, volume, and biomass, are comparable in both Oregon and Washington.

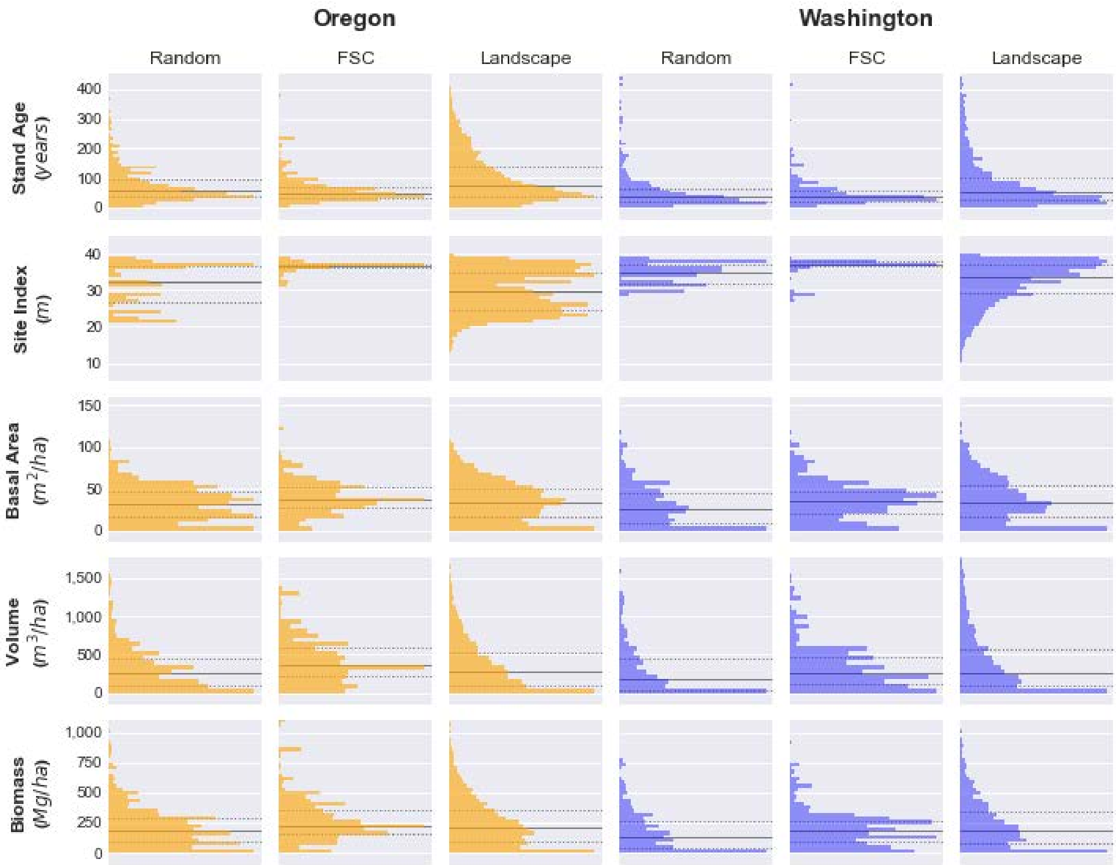

Figure 3. Correspondence between selected parcels and the surrounding landscape. The "surrounding landscape" refers to the extent of the US Environmental Protection Agency Level 3 Ecoregions in western Oregon and Washington which include the sampled parcels. Only areas with forest landcover according to the Gradient Nearest Neighbor Plot Database for 2014 [35] are included in the calculation of these distributions, which are visualized with a histogram based on counts of 30 × 30-m pixels within each area of interest. Horizontal lines in each graph showing the 25th and 75th percentiles (dotted lines) and median (solid line). Site Index refers to the height of dominant Douglas-fir trees at age 50, with values derived from Latta et al. [36].

2.2. Management Systems

In this study, we consider even-aged wood-production-oriented silvicultural systems for Douglas-fir. We do not evaluate other single species systems (e.g., red alder (*Alnus rubra* Bong.)), those which intentionally retain more than one species (e.g., mixtures of Douglas-fir and western hemlock that are also common in western Oregon and Washington), or any uneven-aged management systems in this study. For each parcel, we develop four alternative management scenarios which represent the unique combinations of two alternative objectives and two alternative sets of management constraints. These four management scenarios will be referred to as "BAU" (for Business as Usual), "SHORT~FSC", "LONG~FSC", and "LONG~FPA". These are each described in greater detail below.

2.2.1. Management Objectives

We designed our management scenarios to achieve one of two alternative management objectives: maximize Net Present Value (NPV), or maximize the sustained yield of timber (in terms of cubic volume of sawlogs). For each of these two objectives, we determined an optimal rotation age. "Financially optimal" rotation ages for the NPV-maximizing scenarios were identified as the age at which NPV peaked as the forest grew over time. For each financially optimal rotation, the Soil Expectation Value (SEV), or the present value of perpetual management of the land using that rotation age was also calculated. We calculated "biologically optimal" rotation ages for yield-maximizing scenarios as the age at which the Mean Annual Increment of total cubic volume culminated.

For both objectives, existing stands—with inventory derived from the GNN database—are converted into a Douglas-fir forest based on a financially optimal conversion time determined following Martin [37]. Briefly, the optimal conversion time for each stand was calculated when 'value of forest' peaks starting with current forest conditions. As described by Martin [37], 'value of forest' is calculated as the sum of the NPV of harvestable timber ('value of trees') in each year plus the discounted SEV for the future management of the stand as a Douglas-fir plantation. The initial regeneration/conversion harvest honored the green tree retention and RMZ constraints described below (and in Supplementary Materials) and was followed by planting of Douglas-fir. The varying levels of retention in each scenario produce different forest structure and residual species composition after this initial harvest and over time, although they all move the stands increasingly towards Douglas-fir monocultures across the 100-year simulation timeframe.

2.2.2. Management Constraints

We impose two sets of alternative management constraints for each management objective related to two primary silvicultural choices: the retention of live trees during regeneration harvests; and the limitation or prohibition of harvest activities within Riparian Management Zones (RMZs). The first set of constraints we model represents compliance with the minimum requirements of the Oregon and Washington Forest Practices Acts (FPA) [38,39]. The second set of constraints represents compliance with two of the primary requirements for certification under the Forest Stewardship Council (FSC) program [40].

Although we model these constraints distinctly for each State, we do not capture the full suite of requirements for compliance with either FPA or FSC rules. FSC tends to impose substantial restrictions above and beyond the FPA rules in both States, although the additional requirements for FSC certification are generally more pronounced for Oregon than for Washington, which is primarily due to the difference in limitations on harvesting near streams between Oregon and Washington FPA rules (see Figure 4). To help distinguish our selective choice of management constraints from the full FSC and FPA rules, we denote the management scenarios we simulate as ~FSC and ~FPA, respectively, reserving the unadorned acronyms FSC and FPA to refer to actual FSC-certified parcels or the FSC standard and to FPA rules and regulations.

We also do not apply the full flexibility permitted within FPA or FSC rules. For example, we do not simulate the removal of trees left to satisfy green tree retention in non-riparian stands at the time of a harvest during subsequent entries in neighboring management units, although this appears to be common practice in Oregon and Washington. In our treatment of RMZs, retention requirements are satisfied within each RMZ-designated polygon as a standalone management unit. Although FSC and FPA rules in both Oregon and Washington permit it, we do not count retention in RMZs towards retention requirements in adjacent non-RMZ harvest units. Oregon and Washington FPA rules assign varying RMZ widths and permit varying intensities of harvest within RMZs depending on the stream type (e.g., fish- or non-fish-bearing perennial/seasonal), stream size (Washington and Oregon), and site class (Washington). Although FSC permits single-tree harvest in inner RMZ buffers and group selection in outer RMZ buffers, we have modeled all FSC RMZs as no-touch because neither single-tree nor group selection harvests have been simulated. In this context, the management actions simulated in this study are likely to portray a reduced intensity of management in RMZs and adjacent harvest units than are technically permissible under FPA and FSC rules.

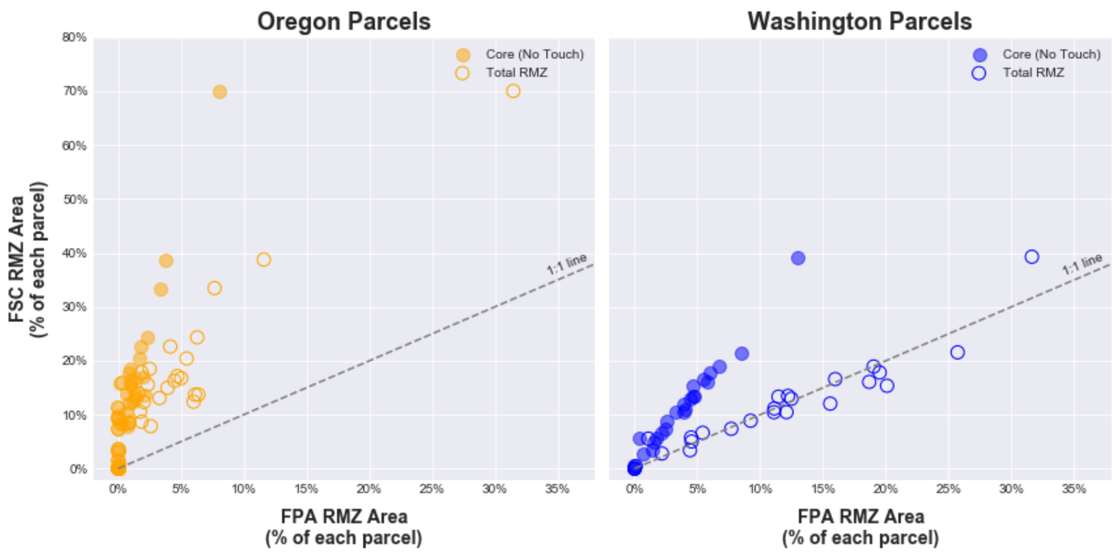

Figure 4. Area encumbered by Riparian Management Zones under FPA and FSC rules for Oregon and Washington. These graphs show the percentage of each parcel that is covered under no-touch/core and total RMZs for both FSC and FPA rules. Points above/below the 1:1 line indicate RMZ buffers cover more/less area under FSC than FPA rules.

Our simulation of ~FPA management scenarios generally errs on the side of conserving more trees during harvests than would be likely following minimal compliance with FPA rules. This is related in part to our choice not to model a variety of exceptions to general RMZ protections (e.g., allowing the successive conversion of hardwood-dominated riparian stands through harvest and establishment of new conifer cover over time).

Our simulation of ~FSC management scenarios also leaves out several important requirements of FSC certification. For example, FSC rules discourage and limit the conversion of natural forests to plantations, which we simulate in our study. FSC certification requires at least 10%–25% of a Forest Management Unit to be maintained and/or restored to a natural or semi-natural state wherever natural ecosystems have been previously converted to plantations. We do not incorporate these constraints in our simulations but recognize that other studies considering set-aside and maximum contiguous harvest area restrictions in FSC have indicated these constraints would lead to additional reductions in harvestable timber volume over time beyond the impacts of those constraints we included in this study [20,27].

2.2.3. Silvicultural Systems

The combination of the two objectives (NPV or MSY) and two management constraints (FPA or FSC) produce four separate management scenarios for each parcel, which are elaborated in Table 1:

1. **BAU** or **SHORT~FPA.** "Business-as-usual" (BAU) management to maximize NPV under the selected constraints of State FPA rules. This scenario represents common practice in production forests of western Oregon and Washington.
2. **SHORT~FSC.** Management to maximize NPV under the green tree retention and RMZ constraints required by FSC. "Short" refers to the relative length of the rotation age compared to MSY-oriented scenarios.

3. **LONG~FPA.** Management to maximize the sustained yield of timber under the selected constraints of State FPA rules. "Long" refers to the relative length of the rotation age relative to the NPV-based management scenarios.
4. **LONG~FSC.** Management to maximize the sustained yield of timber under the selected constraints of FSC certification.

Table 1. Silvicultural systems [1] and treatments applied to each of the parcels.

Activity	BAU	SHORT~FSC [1]	LONG~FPA	LONG~FSC [1]
Planting Douglas-fir	1075 tph (435 tpa)	1075 tph (435 tpa)	1075 tph (435 tpa)	1075 tph (435 tpa)
Commercial Thinning [2]	None	None	@ 55% SDImax [3], thin to 45% SDImax	@ 55% SDImax, thin to 45% SDImax
Regeneration Harvest	@ 38–44 years	@ 38–44 years	@ 75 years	@ 75 years
	retain 10 tph $\geq$ 30.5 cm DBH (4 tpa $\geq$ 12 in DBH)	retain 30% pre-harvest basal area	retain 10 tph $\geq$ 30.5 cm DBH (4 tpa $\geq$ 12 in DBH)	retain 10% of pre-harvest basal area

[1] Although these silvicultural systems are identified as ~FSC scenarios, they are not intended to reflect the silvicultural systems now practiced by existing FSC-certified landowners. In general, silvicultural systems we simulated are more intensive than those practiced by FSC-certified landowners in the Pacific Northwest. [2] Commercial thinning was allowed after age 30, with re-entry as frequently as every 15-years if at least 7 MBF/ha (3 MBF/ac) in harvest volume would be generated and only if the regeneration harvest was not scheduled for at least another 15 years. [3] Methods for determining maximum Stand Density Index (SDImax) are described briefly below and in the Supplementary Materials. DBH: diameter at breast height.

2.3. *Key Performance Indicators*

In this study, we utilize three Key Performance Indicators (KPIs) to compare forest management scenarios: carbon storage, timber output, and discounted cash flow. These KPIs provide information about the potential direct tradeoffs between a newly incentivized ecosystem service, carbon storage, and more traditional KPIs from the forest sector including timber output (which is often used to calculate down-stream economic/job impacts) and cash flow to the landowner.

2.3.1. Carbon Storage in the Forest and Wood Products

To ensure relevance for policymakers considering new voluntary incentive or regulatory approaches to encourage forest carbon storage and sequestration, we quantify carbon storage in this study considering those carbon pools typically included in forest carbon accounting and offset crediting programs. These include above- and below-ground biomass of live trees, standing biomass of dead trees, and carbon storage retained in in-use harvested wood products. This approach is comparable to the accounting framework used by all major forest carbon accounting and crediting programs (e.g., California Air Resources Board (ARB) Forest Carbon Protocol, the Verified Carbon Standard, and the American Carbon Registry). Carbon offset accounting frameworks do not reflect a full Life Cycle Assessment approach and generally omit several carbon pools in the forest (e.g., downed dead wood) and following harvest removals (e.g., use of wood for energy, wood products remaining in landfills), as well as greenhouse gas emissions related to harvesting, transportation, wood products processing and distribution, or the combustion of harvest residues (slash burning). Nevertheless, we believe this carbon accounting framework corresponds to the most likely approach for quantifying parcel-level carbon reductions through forest carbon incentive policies under discussion in Oregon and Washington.

We calculate the carbon storage KPI as the average volume of CO_2-equivalent storage in the forest and harvested wood products pools, net of leakage due to market effects, over a 100-year timeframe. We generally follow the methods defined by the California ARB Forest Carbon Protocol [41]. We apply a single decay factor to account for the long-term average carbon storage in the harvested wood products pool. For this study region, this decay factor corresponds to 42.1% of the carbon removed from a stand in the merchantable portion of harvested trees being retained in wood products, on average, over 100 years. In addition, we follow the ARB Protocol to account for leakage due to market effects (referred to as "Secondary Effects Emissions" in the Protocol), which discounts any additional carbon stored in the forest if there is a decrease in timber output relative to BAU. This effect assumes that a portion of any decline in timber output from a parcel will be made up for by increased harvesting in other locations, resulting in a "leakage" of the additional carbon stored in the "project area". The ARB Protocol assigns a 20% leakage factor to the difference of harvest removals in a given year between the projected scenario and a BAU (or "baseline") scenario if the projected scenario has generated a lower cumulative harvest volume than the baseline scenario up to that point in time. We diverge from the ARB Protocol's methods that establish a "baseline" for carbon offset crediting using a long-term average of the BAU scenario that must be at least as high as the average carbon storage in comparable forest types in an "Assessment Area". We do not impose a long-term average constraint on the BAU scenario for our calculation of additional carbon storage in alternative scenarios, but rather make these calculations using the dynamic values of carbon storage in both the BAU and the alternative management scenarios over the 100-year simulation timeframe.

2.3.2. Cumulative Timber Output

The timber output KPI is calculated as the cumulative sawlog volume (using Scribner boardfoot measure) of merchantable wood produced by each management scenario. Volumes are included for the following species: Douglas-fir, Sitka spruce (*Picea sitchensis* (Bong.) Carrière), western hemlock, grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.), noble fir (*Abies procera* Rehder), Pacific silver fir (*Abies amabilis* (Douglas ex Loudon) Douglas ex Forbes), western redcedar, yellow cedar (*Callitropsis nootkatensis* (D. Don) Oerst. ex D.P. Little), red alder, and bigleaf maple (*Acer macrophyllum* Pursh).

Merchantable boardfoot volume is included for softwood trees with a minimum diameter at breast height (DBH) of 22.86 cm (9 in) to a minimum top diameter inside bark (DIB) of 15.24 cm (6 in). Merchantable boardfoot volumes are also included for two hardwood species—red alder, and bigleaf maple—with a minimum DBH of 27.94 cm (11 in) up to a minimum top DIB of 20.32 cm (8 in). Boardfoot volumes are determined using 9.75 m (32 ft) log equations for softwoods and 4.88 m (16 ft) log equations for hardwoods. All boardfoot volume calculations include a deduction for a 0.3 m (1 ft) stump. We also impose log volume adjustment factors to correct Scribner volume overestimation observed when using the National Volume Estimator Library (NVEL) Behre's hyperbola equations available in FVS [42]. Boardfoot "defect" adjustment factors were calculated for several DBH classes for each merchantable tree species. The scales of these adjustments were determined by quantifying the average correction needed to have NVEL estimates match those produced by the regional volume equations utilized in the US Forest Service's Forest Inventory & Analysis Program [43]. These adjustment factors are presented in the Supplementary Material.

2.3.3. Discounted Cash Flow

For our third and final KPI, we calculate discounted cash flow using an annual discount rate of 5%, which was chosen based on recent industry presentations/reports [44,45]. Timber sale revenues are calculated using delivered log prices based on a recent log price report from the Washington Department of Natural Resources [46] and are presented in Table 2. Management costs were determined based on a recent survey of industrial forest landowners in the Pacific Northwest [47] and are presented in Table 3. We calculate discounted cash flow using real discount rates and prices; inflation is not reflected in these calculations.

Table 2. Delivered log prices [1].

Species	$/MBF
Douglas-fir	796
Sitka spruce	450
Western hemlock	640
Noble fir	640
Grand fir	640
Pacific silver fir	640
Yellow cedar	640
Western redcedar	1263
Red alder	852
Bigleaf maple	499

[1] Derived from February 2018 log price report for Washington "Coast Marketing Area" [46].

Table 3. Management costs.

Activity	$	Per
General administration	86	ha/year
Site preparation	210	ha
Tree planting	0.73	seedling
Brush control (@ age 5)	334	ha
Harvest administration	5	MBF
Hauling	100	MBF
Road maintenance	15	MBF
Ground-based harvest:		
Regeneration harvest	150	MBF
Commercial thin	175	MBF
Cable logging:		
Regeneration harvest	200	MBF
Commercial thin	300	MBF

2.3.4. Embodied Carbon

We also present a hybrid indicator for the "embodied carbon" of wood products generated in each management scenario, calculated as the average carbon stored in the forest and wood products divided by the cumulative amount of timber produced over the modeling timeframe (100 years). This metric provides an indicator of the embedded carbon footprint for timber generated under each alternative management regime, which may be useful in the same context that greenhouse gas displacement factors can be used to quantify the benefits of utilizing wood in place of more carbon-intensive building materials [23], or in the context of Environmental Product Declarations, which seek to quantify the environmental impact of products commonly considered by builders.

2.3.5. Incentives or Price Premiums that Close the Financial Gap with BAU

Alternatives to BAU forest practices are generally expected to provide a lower return on investment given current market conditions and policies. In many forest carbon offset standards, this assumption is often explicitly identified as a financial barrier to the adoption of new practices and integrated into the definition and assessment of additionality [48–51]. A variety of alternative revenue strategies, including the sale of conservation easements and carbon offsets, as well as the delivery of higher-value logs from extended rotations or commercial thinning harvests timed to favorable market conditions are often considered as incremental approaches to help close and/or overcome these financial barriers [51].

We quantify two options for reducing the financial gap between BAU and alternative management scenarios. The first option we consider is a premium on wood sold. We quantify the premium on wood as a multiplier to the periodic gross revenue from the sale of timber. This could correspond, for example, to a premium based on the production of logs with a higher value per volume measure, or to a premium based on consumer willingness-to-pay for a third-party certification such as FSC. The second option we consider is an incentive for additional carbon stored in the forest and harvested wood products. In this approach, we add new revenue based on the difference in credited carbon stored (in the forest and wood products, net of leakage) between each alternative scenario and BAU. In the first five-year simulation period, the difference between an alternative management scenario and BAU is calculated and rewarded. In all successive periods, the change in carbon stored in each alternative management scenario versus the change of carbon stored in the BAU scenario is rewarded. The additional income provided by the wood premium or carbon value is discounted to present value. We utilized a simple optimization using the scipy Python package to search for the incentive value which minimizes the squared difference in NPV at the end of 100 years between an alternative management scenario and BAU for each parcel individually.

2.4. Growth-and-Yield Simulation

We conducted growth-and-yield modeling using the Pacific Northwest Coast (PN) variant of the Forest Vegetation Simulator (FVS) [52–54] with Database and ECON extensions employed to streamline data input/output and for economic calculations [37,55].

We calibrated FVS default growth and mortality parameters based on comparison of growth projections of Douglas-fir plantations established from bare ground with historical yield tables [56–61], long-term/permanent plot records [62,63], and regional forest inventory data [64] (Supplementary Material). We identified modifications for the maximum Stand Density Index (SDI_{max}) to adjust competition-related mortality rates, background mortality rates prior to age 30, and multipliers to reduce the annual basal area increment of large trees. These adjustments to default FVS-PN model behavior are our best attempt to strike a conservative balance capturing rapid growth and yield apparent from contemporary intensive Douglas-fir plantations [61] for young stands without allowing the relative gains in growth and productivity in these young stands to persist into older age. This approach directs yields in stands older than those observed in intensive plantation field plots [61] back towards the median range of values in Douglas-fir forests observed across the landscape of western Oregon and Washington from historical yield tables, permanent plots, and FIA data. By forcing the trajectory of advanced growth of younger plantations back down towards historical trends, we run the risk of under-estimating the potential timber yield and harvest revenue these intensively managed stands might be able to sustain if they were allowed to grow to ages beyond “financial maturity”. This decision was made primarily because little to no inventory data are currently available for intensively-managed plantations using contemporary silvicultural practices and seed sources beyond the range of 40–50 years.

To identify the optimal rotation ages for each of our management scenarios (Table 1), we simulated the establishment and growth of Douglas-fir plantations from bare ground on a relatively flat slope (10%) and a steep slope (40%) for each Douglas-fir 50-year Site Index value ranging from 15.2 m (50′) to 48.7 m (160 ft) in increments of 1.5 m (5 ft). The age at which NPV peaked for each slope-by-productivity combination was identified as the “financially optimal” rotation age used for our BAU and SHORT~FSC scenarios. Our calibration of FVS induced a distinct downward bend in timber volume growth around age 35–40 as stands approached SDI_{max}. We applied a moving average function to smooth the NPV curve derived from these simulations and identified financially optimal rotation ages of 38–44 years, depending on Site Index and slope (stands with steeper slopes had slightly later rotation ages than those on flat ground). The age of culmination for Mean Annual Increment (MAI) in terms of total cubic volume was identified as the “biologically optimal” rotation age for our LONG~FPA and LONG~FSC scenarios. These longer-rotation scenarios included commercial thinning to capture density-driven mortality after age 30 and resulted in a rotation age of 75 years for all stands regardless of Site Index.

We conducted a 100-year simulation using a 5-year time step for every management unit (out of 10,068) across the 64 parcels. We modeled every prescription available (4 non-riparian, 1 “grow only”, and 20 riparian prescriptions meeting the distinct retention requirements of each stream type, size, etc.) for each management unit, producing a total of 252,150 simulations. The outputs from these simulations were then scaled to the area assigned to each treatment for each stand.

Many of the KPIs and other indicators of interest across the parcels are not normally distributed. As such, we report the median and percentile ranges for these indicators rather than a mean and standard error.

Computing Environment for Simulations, Data Analysis, and Visualization

We ran FVS simulations on a 32-core Linux server using the latest version of open-fvs built from source [65]. We utilized PostgreSQL databases for FVS input and output to permit batch modeling with an asynchronous parallel processing workflow coded using the Python programming language. All code developed by the authors for implementing this processing workflow is open-source and has been published by Ecotrust on GitHub [66]. The parallel processing workflow enabled the completion of these 252,150 FVS simulations in 6–7 h. Data analysis and visualization has been conducted using packages in both the Python and R languages. The outputs of FVS simulations, expanded to a per-area basis for each parcel, are included in the GitHub repository, along with a Jupyter Notebook [67] containing all the code necessary to generate the graphs and tables included in this article. Utilizing the Binder service, which is linked from the landing page of the GitHub repository for this project [66], a copy of this Jupyter Notebook can be launched in the cloud with the relevant computing requirements pre-installed and configured to allow for the reproduction of our quantitative analysis and visualizations without the need to download or install any software.

3. Results

3.1. Calibration of FVS

Our calibration of the FVS-PN variant for Douglas-fir plantations against independent field data and yield tables revealed a consistent over-prediction of cubic and boardfoot volumes using default FVS parameterization. These over-predictions were observed at the individual tree level, as well as for volume growth and carrying capacity metrics at the stand level. The use of an uncalibrated model would have resulted in much greater estimates of future volume and carbon, particularly for older stands. The parameterization we identified through trial and error follows plantation growth curves fairly well through financial maturity (age 40), after which point the projected metrics gradually return into the range of average conditions observed in natural stands. Outputs from the default and calibrated FVS-PN projections are presented in the Supplementary Material for the height of dominant trees, number of trees per acre, basal area, quadratic mean diameter, cubic volume, Scribner boardfoot volume, Stand Density Index, and Curtis Relative Density. A series of yield tables for these metrics using the calibrated model are also provided.

3.2. Simulated Forest Dynamics

The optimal conversion time for most stands was identified as the first simulation cycle, with 77% of non-riparian acreage on Oregon parcels and 81% of non-riparian acreage in Washington converted in the first five years of simulation; over 90% of non-riparian areas in both states underwent the conversion harvest within 20 years of the start of the simulation. This rapid conversion resulted in saw-tooth outputs characteristic of stand-level simulations, with the age-based harvest triggers clearly apparent across all 64 parcels (Figure 5).

Over the 100-year simulation period, the greater green tree retention in ~FSC scenarios produced successive accumulation of carbon stored in trees over time, while the shorter ~40-year rotations of the BAU scenario generally reset the amount of carbon stored in trees to a low and consistent level at each harvest. The use of a fixed decay factor generated a step-wise increase for carbon stored in harvested wood products with each successive harvest for the ~40-year rotations (BAU and SHORT~FSC).

For both the BAU and LONG~FPA scenarios, carbon stored in wood products began to rival that stored in trees by the end of the simulation; for both the ~FSC scenarios, the amount of carbon storage in trees was almost always higher than in products.

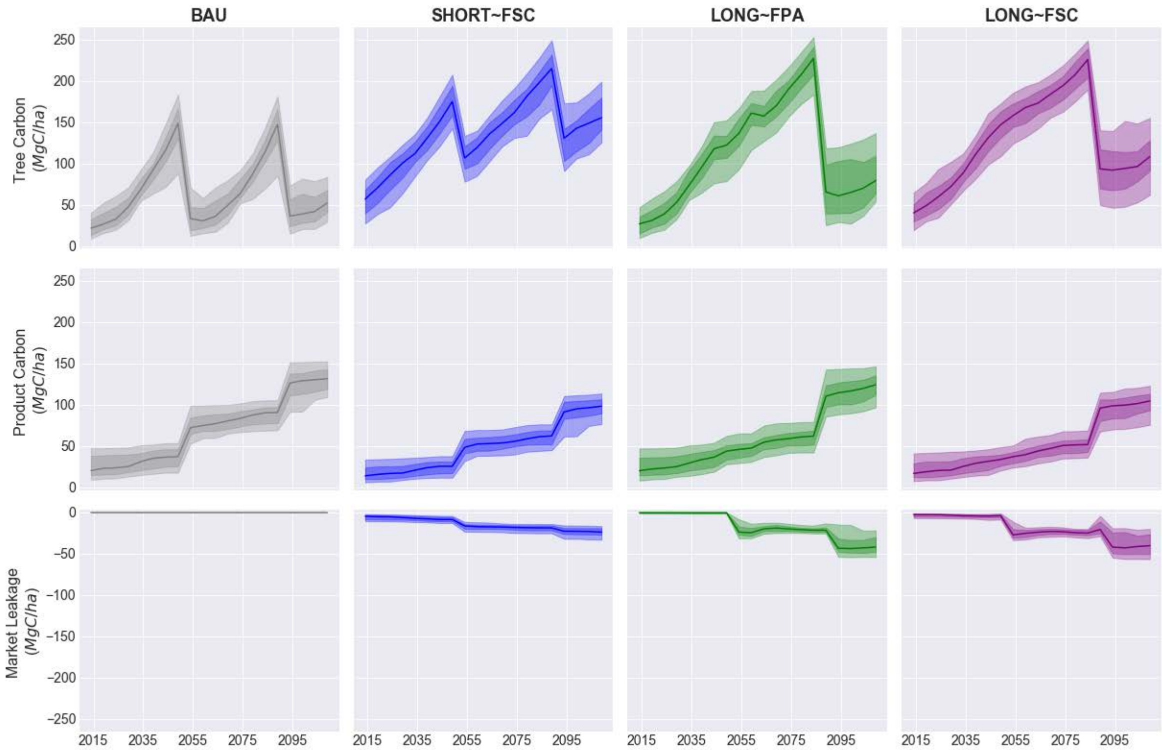

Figure 5. Carbon stored in three primary categories of pools/emissions under four alternative management scenarios. The dark line in each graph represents the median value over time across the 64 parcels. The shaded areas correspond to the 25th–75th percentile range (darker), and the 10th–90th percentile range (lighter).

Leakage due to market effects was generally small compared to the amount of carbon stored in trees or products, and occasionally resulted in periodic calculations of modest positive market leakage. This positive leakage effect emerges in cases where an alternative management scenario has produced less cumulative timber output than the BAU scenario up to a certain point in time, but generates a larger periodic output than BAU for one or more years, and can be seen for the LONG~FPA and LONG~FSC scenarios where cumulative market leakage follows brief upward movements (becomes less negative) for short periods (Figure 5).

An inspection of stand images produced using the Stand Visualization System [68] indicated that the relatively high levels of green tree retention in the SHORT~FSC scenario (30% at each regeneration harvest) often resulted in the development of two-aged stand structures by the end of 100-year simulation period, while the longer rotation and BAU scenarios usually maintained a single-aged stand structure (data not shown).

3.3. Key Performance Indicators

The dynamics of timber output, carbon storage, and discounted cash flow over the 100-year simulations for each scenario are displayed in Figure 6.

In general, the BAU scenario usually performed the best under the two traditional forestry KPIs (timber output and discounted cash flow), and the worst under the carbon KPI. The distinct contributions to the KPIs by the individual constraints on green tree retention and riparian buffers can also be isolated and are displayed in Table 4. For example, a shift from ~FPA green tree retention levels in the BAU scenario to ~FSC retention levels showed a larger impact on carbon storage, timber output, and NPV than the expansion of riparian buffers did.

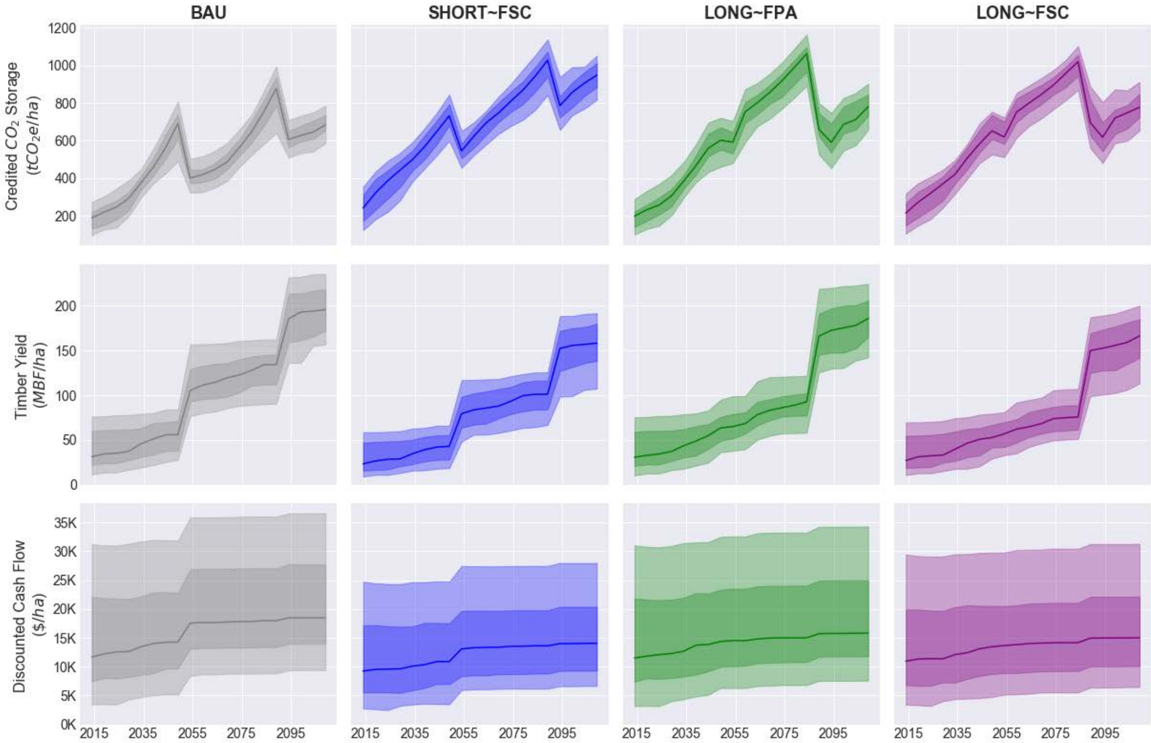

Figure 6. Dynamics of three KPIs over 100 years under four alternative management scenarios. The dark line in each graph represents the median value over time across the 64 parcels. The shaded areas correspond to the 25th–75th percentile range (darker), and the 10th–90th percentile range (lighter).

Table 4. Isolated impacts of green tree retention and RMZ widths constraints on KPIs for each scenario.

	SHORT~FPA			**SHORT~FSC**			**LONG~FPA**			**LONG~FSC**		
OREGON	*MBF*	*tCO_2e*	*$K*	*MBF*	*tCO_2e*	*$K*	*MBF*	*tCO_2e*	*$K*	*MBF*	*tCO_2e*	*$K*
~FPA Buffers	199	497	19.1	169	634	15.3	197	608	17.1	183	595	15.9
~FSC Buffers	176	553	18.0	153	679	14.3	163	686	15.7	168	646	15.3
WASHINGTON												
~FPA Buffers	185	518	18.0	166	663	14.6	174	639	15.6	170	620	15.5
~FSC Buffers	178	527	17.2	159	659	14.0	158	656	13.9	165	616	14.4

Each set of six cells displays the median of each KPI on a per hectare basis over the 100-year simulation period for each management scenario, with riparian rules following either ~FPA or ~FSC. $K refers to thousands of US dollars of Net Present Value. Both ~FPA scenarios involve the same green tree retention (10 tph/4 tpa) during regeneration harvests, while SHORT~FSC retains 30% of pre-harvest basal area and LONG~FSC retains 10%. To quantify the isolated effects of imposing 30% green tree retention versus minimum ~FPA retention for a given state, for example, compare the first row beneath SHORT~FPA with those in the *first* row beneath SHORT~ FSC.

The long-rotation scenarios generated a lower yield of cumulative timber volume over time compared to the short-rotation scenarios. However, the long rotation scenarios carried a higher standing volume of harvestable timber than the shorter rotation scenarios. The relatively rapid conversion across the parcels and subsequent homogenization of age classes likely exaggerated an effect from the fact that the shorter rotations were able get two full harvest cycles into the simulation timeframe while the long rotation scenarios did not. Considering the standing boardfoot volume in addition to the cumulative harvested volume by the end of the simulation period, the longer rotations showed higher totals: the median standing plus harvested timber volume was 288 MBF/ha among parcels for the LONG~FPA scenario and 268 MBF/ha under the BAU scenario; LONG~FSC had a median of 618 MBF/ha while SHORT~FSC had median of 601 MBF/ha. These values demonstrate higher Mean Annual Increment for the long rotations compared to the short rotations. Furthermore, the different conclusions that might be drawn from considering yields alone versus Mean Annual Increment suggest that a more evenly distributed set of age classes across the landscape, often referred to as a "regulated" harvest schedule, would translate into higher yields for the longer-rotation scenarios. A more phased approach across the landscape to the conversion from initial forest conditions than the one we simulated may have demonstrated this case more directly.

The greater green tree retention and wider and more restrictive RMZ rules of the ~FSC scenarios corresponded with higher carbon storage at the expense of lower timber yields and NPV than their ~FPA counterparts within our 100-year timeframe. Compared to Oregon, Washington showed modestly higher carbon storage, lower yields, and lower NPV for all scenarios (based on median values of KPIs across the simulated parcels). Looking at the KPIs for the alternative scenarios relative to BAU across both States (Figure 7), LONG~FPA scenarios had median values of 22.5% more carbon stored, 4.3% less timber generated, and 11.7% lower NPV; LONG~FSC yielded 25.5% more carbon, 15.2% less timber, and a 20.6% lower NPV; and SHORT~FSC yielded 32.4% more carbon, 19.0% less timber, and 25.3% lower NPV. LONG~FPA also provided a relatively tighter clustering of points compared to BAU than did either of the ~FSC scenarios. LONG~FPA had overall lower variation in stand-level response when compared to the ~FSC scenarios; the ~FSC scenarios increased the likelihood of generating higher carbon storage and lower NPV.

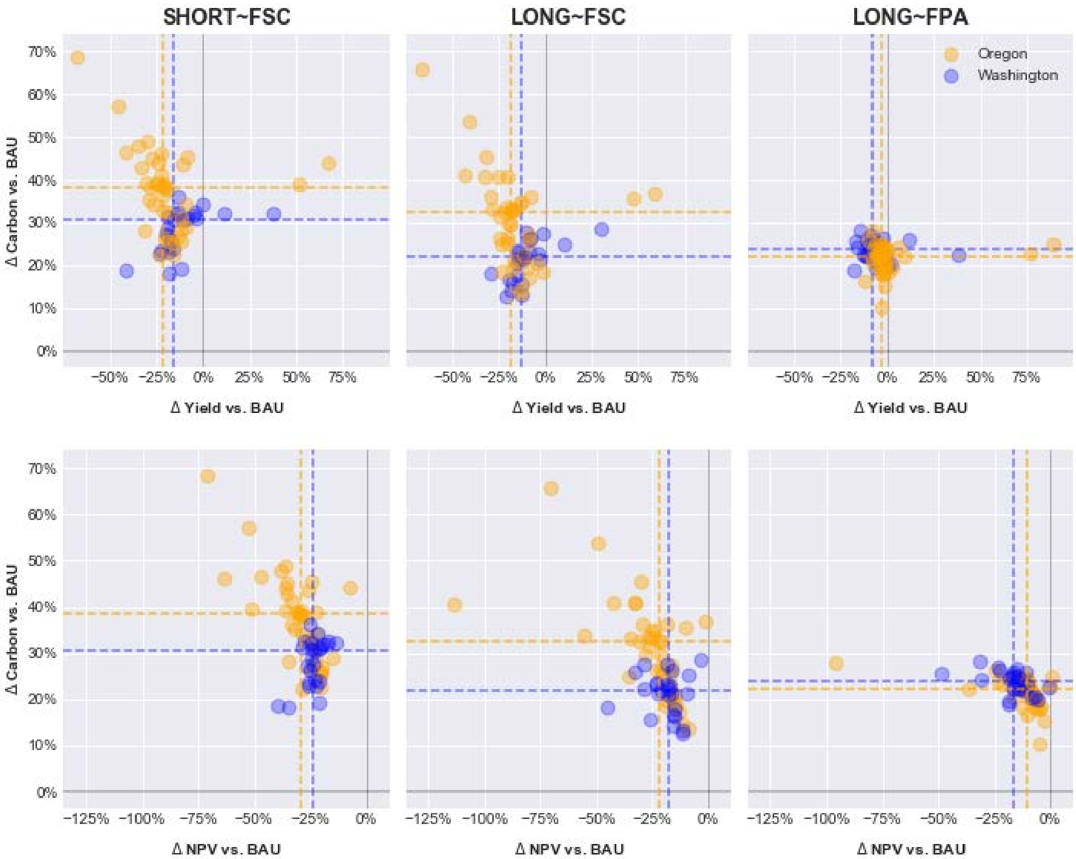

Figure 7. Shifts in timber yield, carbon storage, and cash flow relative to business-as-usual (NPV~FPA) for each of the three alternative scenarios. The top row of graphs shows carbon and timber yield shifts; the second row shows carbon and cash flow shifts. Each point corresponds to one of the 64 simulated parcels. The dashed lines represent the median value.

Per MBF of wood produced, ~FSC scenarios always had a larger embedded carbon value. In Oregon, BAU scenarios generated carbon storage of 2.4 tCO_2e per MBF produced over 100 years (median of the 64 simulated parcels), while SHORT~FSC, LONG~FSC, and LONG~FPA stored 4.2, 3.9, and 3.1 tCO_2e per MBF. In Washington, BAU stored 2.9 tCO_2e per MBF, while SHORT~FSC, LONG~FSC, and LONG~FPA stored 4.1, 3.9, and 3.7 tCO_2e per MBF. This indicates mid-range estimates for an implicit embedded carbon benefit of 1.5 to 1.8 (Oregon) or 1.0 to 2.1 (Washington) of tCO_2e per MBF for logs produced under ~FSC constraints relative to those produced under current common practice.

3.4. Values that Close the Financial Gap with BAU

The values of a prospective premium on wood products or carbon incentive program required to close the financial gap between the alternative management scenarios and the BAU scenario are shown in Table 5. In general, LONG~FPA would be able to break-even with BAU with the support of more modest premiums or incentives than those required for either of the ~FSC scenarios.

Table 5. Additional value for wood and carbon storage required to close the financial gap of alternative management scenarios with the BAU scenario.

	SHORT~FSC			LONG~FSC			LONG~FPA		
OREGON	*25%*	*median*	*75%*	*25%*	*median*	*75%*	*25%*	*median*	*75%*
Wood Premium (%)	9.8	15.0	21.3	3.0	5.2	9.8	0.0	1.4	2.5
Carbon Value ($/$tCO_2e$)	27.90	41.21	49.43	30.84	42.68	51.50	0.00	17.94	23.99
WASHINGTON									
Wood Premium (%)	8.7	10.7	12.0	5.1	5.9	9.6	2.3	4.7	6.2
Carbon Value ($/$tCO_2e$)	10.96	26.03	39.56	26.91	32.76	40.03	20.61	33.83	38.02

Values shown are the 25th, 50th, and 75th percentiles for parcels in each state.

4. Discussion

4.1. Fundamental Importance of FVS Calibration

Under default parameterizations, the FVS-PN variant projected wildly unrealistic volume and value growth for the Douglas-fir plantation scenarios considered in this study. Comparisons of projected volumes with independent datasets including historical yield tables, extensive publicly-available forest inventory data, and long-term permanent plot records allowed the growth-and-yield projections to be reined in significantly. This required the authors to make explicit decisions and balance tradeoffs in model performance to reasonably capture growth in young and mature Douglas-fir management scenarios of interest. Although the developers of FVS have encouraged and suggested quality control and quality assessment best practices to calibrate or validate the model [69], and a host of calibration and validation examples exist in the literature, the potential scale of errors from the use of FVS default settings are not common knowledge among model users. Studies intended to be policy- or management-relevant using FVS without describing how they calibrated or validated the model may be vulnerable to large errors, a vulnerability that may be particularly concerning if climate change factors are integrated into FVS projections where little to no independent validation data may be available. For example, although forest carbon offset programs often impose substantial costs to minimize the potential variability or error in field measurement, they tend to ignore much larger sources of variability associated with the use of growth-and-yield models over a century-scale timeframe, whether or not climate change is acknowledged [21].

The calibration effort we present in the Supplementary Materials strikes a careful balance between estimates of rapid plantation growth at younger ages returning to landscape-level averages over time. These tradeoffs were considered explicitly with the goal of increasing our confidence that the values we were primarily interested in quantifying (e.g., the tradeoffs in carbon storage and timber output between long- and short-rotation scenarios) could be done conservatively, that is, with a reduced likelihood for overestimation of the effects of alternative management.

4.2. Tradeoffs in Timber Production, Carbon Storage, and Cash Flow

The observation that all alternative scenarios, for every parcel evaluated, stored a substantially higher volume of carbon in the forest and in harvested wood products highlights the potential for a variety of management options to improve the carbon storage performance of Douglas-fir management beyond BAU practices. However, the financial analysis we present highlights the significant financial hurdle that these alternative management approaches face. Our findings of NPV under ~FSC scenarios on the order of 25% lower than BAU is consistent, but on the low end of estimates produced by others who have considered a broader suite of constraints required for FSC certification for Pacific Northwest Douglas-fir management [20,27].

The tighter clustering of LONG~FPA outcomes relative to the ~FSC scenarios (Figure 7) indicates that the greater retention of trees both in- and out-side of RMZs under the ~FSC scenarios (including species other than Douglas-fir), may introduce a substantial amount of variability in the projected outcomes for all KPIs. The diversification of species and size classes may offer both positive and negative aspects to future management outcomes. Any impacts of natural disturbances or climatic change, which are not simulated here, would be expected to produce different effects in homogenous and heterogenous stands; the more tightly predictable outcomes for a homogenous stand may also involve a greater exposure to uncertain future risks.

4.3. Multiple Financial Gap-Closing Strategies Would Likely Need to be Used for FSC to Compete with BAU

The analysis of options to close the financial gap between alternative management scenarios and BAU offers a practical set of indicators that inform their financial desirability (and presumably, the likelihood and scale with which these alternative practices could be implemented with supportive market conditions or policies). A premium on wood produced under these alternative management scenarios on the order of 15%–20% could be generated from the sale of higher quality larger logs produced by longer rotations as well as consumer willingness to pay for third-party certification, although neither of these options are consistently available in the market and both are likely to involve substantial marketing challenges.

Production and price premiums for higher-quality appearance-grade wood from larger-diameter logs have declined in the Pacific Northwest since the 1960s with the transition away from harvesting old-growth and toward shorter rotations of plantations [5,70]. Premiums for larger-sized and higher-quality logs now occur sporadically and fluctuate significantly with both domestic and international market conditions. In the absence of sustained demand, larger logs now commonly face a price penalty rather than a premium, as many sawmills in the region have evolved to more efficiently process the supply of smaller logs more typical from the region's industrial forestlands. Premiums for export-quality or other high-value domestic log sorts are thus likely to offer landowners relatively unpredictable and short-lived opportunities to close the financial gap of alternatives to BAU management over time.

A growing interest among green builders for sustainable wood products may also offer a complementary value stream, although the potential demand for certification among green builders remains poorly understood. There is generally little evidence from the Pacific Northwest of price premiums for FSC-certified wood sometimes present in the retail setting translating up the supply chain into higher log prices received by FSC-certified landowners.

It is important to note that the options to close the financial gap between alternative management scenarios and BAU represent the value delivered to the landowner, not the retail price or premium paid by a consumer. This implies that any additional production or transaction costs required to deliver that value to the landowner would require even higher prices and premiums than those estimated here. For example, the market price of carbon required to close the financial gap between

~FSC scenarios and the BAU scenario would need to reflect the high startup and transaction costs for carbon market participation that present a substantial financial barrier to broader carbon market participation, particularly for smaller landholders [71–74]. For example, an analysis of the break-even carbon price for a 65-year rotation to match the NPV of a 45-year rotation in similar forest conditions that also included a more thorough accounting of carbon project development costs was $49.87 per tCO_2e [21]. These carbon prices are several times higher than those observed in prevailing markets [26], and highlight what van Kooten observed more than twenty years ago: "In general, inclusion of the external benefits from carbon uptake results in rotation ages only a bit longer than the financial (Faustmann) rotation age" [6].

4.4. Policy Implications

4.4.1. State FPA Rules Fundamentally Affect the Landscape and New Policy Opportunities

The difference between current State FPA regulations, particularly regarding riparian protections, have important consequences for financial performance, carbon storage, and the potential for new market- and non-market-based forestry policies to influence how the land is managed. The gap between FPA and FSC rules in Washington is narrower than it is in Oregon, which was clearly shown by the KPIs among our ~FSC and ~FPA simulations. The permission of more intensive harvest practices under Oregon FPA rules creates a higher opportunity cost for alternative management scenarios than is the case in Washington. As such, higher premiums for wood and higher values for carbon storage would be needed to shift forest management practices in Oregon compared to Washington in the absence of any changes to forest practices regulations.

In general, policies encouraging or incentivizing increased riparian protections, green tree retention, or the extension of rotation ages are likely to translate into greater carbon storage. A comparison of the isolated effects of the RMZ extension and increased green tree retention constraints demonstrates the expanded riparian protections offered a smaller impact on timber output and financial performance than would be accomplished by increasing FPA green tree retention levels from current minimum requirements to the 10% or 30% of pre-harvest basal area imposed by FSC. However, the greater decrease in timber output and financial performance involved with increased green tree retention also directly translated into proportionally higher carbon storage. Both green tree retention and greater RMZ protections are likely to correspond to other additional values including water quality and habitat for fish and wildlife that are not quantified here. Although carbon storage is the easiest of these ecosystem services to quantify, it is often these other values which form the basis for policies encouraging conservation practices. Additional carbon storage could be more reasonably considered as a co-benefit rather than the primary objective or indicator for public investments or regulation to encourage these practices.

4.4.2. FSC-Certification Appears to Offer a Clear Surrogate for Increased Forest Carbon Storage

The greater green tree retention and RMZ protections involved in FSC certification translated directly into higher average carbon storage in every parcel we evaluated, even after accounting for market effects of leakage. The approaches we have taken to modeling the policies and growth dynamics for these managed forests indicate that FSC-certified wood carries an embedded carbon benefit relative to wood produced by current common practice in the region. Our analysis does not employ a full Life Cycle Analysis, as is commonly involved in Environmental Product Declarations, but nevertheless offers a clear indicator that FSC-certification offers a reasonable assurance of improved carbon balance compared to BAU.

Considering the high transaction costs that have formed a substantial barrier to participation in carbon markets [21,30,71–73,75], FSC-certification may offer a simple and cost-effective surrogate for directly identifying and rewarding landowners who follow forest practices that sequester additional carbon relative to BAU (and that also are likely to generate additional ecosystem service values, such as improved water quality and wildlife habitat). FSC-certification has been much more accessible to non-industrial landowners than carbon markets have been to date, and simpler incentive models similar to existing US Farm Bill programs may offer a more accessible approach to engage more landowners in forest conservation and management. Conservation incentive and carbon rental approaches have been considered before in the literature [73,74,76], proposed recently by collaborative forest policy working groups [77,78] and may be particularly relevant for new policy development if increasing accessibility to landowners or increasing the area of forestland engaged in forest carbon programs are important policy objectives.

4.4.3. Lower Variability in LONG~FPA Suggest Extending Rotation Ages alone as a Viable Option

The LONG~FPA scenarios showed reduced variability in timber, carbon, and financial KPIs than either of the ~FSC scenarios. We believe this reduced variability is likely to correspond to the lower green tree retention, particularly for species other than Douglas-fir, in the LONG~FPA scenario compared to the ~FSC scenarios. The timber premium and carbon values required to close the financial gap with BAU were much smaller for LONG~FPA, and a substantial number of parcels, particularly in Oregon, were projected to perform better than BAU under all three KPIs (as demonstrated by a timber premium of $0 for 25% of Oregon parcels to meet or exceed the NPV of the BAU scenario).

Our simulations suggest that landowners pursuing a LONG~FPA scenario may have less uncertainty in the outcomes for these KPIs than those pursuing the SHORT~FSC or LONG~FSC scenarios. Drawing more general conclusions about the long-term effects of management alternatives on forest risks and vulnerabilities would need to extend beyond those values considered here and be difficult to quantify. The homogenization of existing forest composition may involve increased exposure to risks from maintaining a single-aged monoculture of Douglas-fir such as pests or diseases, or regeneration failure due to severe weather or drought. Longer rotations carry a larger timber value over an extended period and may thus entail additional risks for potential damage from fire, insects, disease, or severe weather, all of which may be affected by climate change [79]. Management actions that diversify forest structure and composition may also alter a forest's resistance and resilience to environmental changes and disturbances. Ultimately, landowners, forest managers, and policymakers will continue to navigate and judge complex interactions among these risks, value systems, and the uncertainty of our changing climate into the future. The research presented here offers insights into the tradeoffs and options for balancing a few the Key Performance Indicators now commonly being considered in management and policy decisions.

5. Conclusions

Our work clearly demonstrates that the adoption of certain forest practices including expanded riparian protections, increased green tree retention, and the extension of rotation ages can translate into substantially higher carbon storage than contemporary common practice for Douglas-fir management in the Pacific Northwest. However, these practices, particularly if adopted in combination, will also generally correspond to reductions in financial viability that may be important considerations for landowners, forest managers, and policy makers to quantify and balance. Estimates for the balance between these tradeoffs may be particularly sensitive to choices in growth-and-yield or other modeling approaches employed, and clear documentation of the assumptions and calibration of models used for these purposes should be considered a critical component for science- or evidence-based policy or forest management decisions.

The combination of forest practices required for FSC certification always stored more carbon than business-as-usual and produced an embodied carbon benefit that may offer a useful indicator for wood consumers concerned with quantifying and reducing the impact of their purchasing decisions, independent of any potential benefits derived from the substitution of wood for more carbon- or energy-intensive building materials. FSC certification also offers a useful case illustrating the potential for certification options simpler than current carbon offset crediting programs for market- and non-market-based policies to identify and incentivize landowners for additional forest carbon sequestration.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/9/8/447/s1, Table S1. FVS keyword modifications; Table S2. Mean percent defect incorporated into FVS for each species diameter at breast height; Table S3. Yield Table: Dominant Height (feet), 40 tallest trees per acre; Table S4. Yield Table: Trees per Acre; Table S5. Yield Table: Basal Area (sq. ft. per acre); Table S6. Yield Table: Quadratic Mean Diameter (inches); Table S7. Yield Table: Cubic volume including top and stump (hundreds of cubic feet per acre); Table S8. Yield Table: Boardfoot Volume, Scribner Rule (thousands of boardfeet per acre); Table S9. Yield Table: Stand Density Index; Table S10. Yield Table: Curtis Relative Density; Table S11. Buffer widths for Riparian Management Zones under FPA and FSC Rules; Table S12. RMZ length for 50-foot core (no-touch) buffer area for Type Np streams that intersect with Type S or Type F streams, Washington State; Table S13. Minimum Retention for Inner RMZ Buffers on Type F streams, Washington State; Table S14. Oregon FPA "Standard Targets" for Retention in Inner RMZ Buffers; Table S15. Oregon FPA "Alternative Targets" for Retention in Inner RMZ Buffers; Figure S1. Default FVS Parameterization comparing PN variant output to measured stands (Part 1 of 3): Trees Per Acre and Basal Area per Acre; Figure S2. Default FVS Parameterization (Part 2 of 3): Quadratic Mean Diameter and Total Cubic Volume; Figure S3. Default FVS Parameterization (Part 3 of 3): Stand Density Index and Gross Boardfoot Volume; Figure S4. Modified FVS Parameterization (Part 1 of 3): Trees Per Acre and Basal Area per Acre; Figure S5. Modified FVS Parameterization (Part 2 of 3): Quadratic Mean Diameter and Total Cubic Volume; Figure S6. Modified FVS Parameterization (Part 3 of 3): Stand Density Index and Gross Boardfoot Volume; Figure S7. Comparisons of the area encumbered by FSC and FPA RMZs for Oregon and Washington.

Author Contributions: Conceptualization, B.D. and D.D.D.; Methodology, D.D.D., S.L. and G.J.E.; Software, D.D.D. and S.L.; Validation, D.D.D., S.L., and G.J.E.; Formal Analysis, D.D.D. and S.L.; Investigation, D.D.D. and S.L.; Resources, D.D.D. and S.L.; Data Curation, D.D.D. and S.L.; Writing-Original Draft Preparation, D.D.D. and S.L.; Writing-Review & Editing, D.D.D., S.L., G.J.E., and B.D.; Visualization, D.D.D. and S.L.; Supervision, D.D.D., G.J.E., and B.D.; Project Administration, D.D.D.; Funding Acquisition, B.D., D.D.D., G.J.E.

Funding: This research was supported by grants to Ecotrust from the Bullitt Foundation and MillsDavis Foundation. Funding for this work was also provided to David D. Diaz including a graduate fellowship from the University of Washington College of the Environment, a scholarship from the ARCS Foundation and from the University of Washington School of Environmental and Forest Sciences (George Meagher Scholarship, J.H. Bloedel Forestry Research Fellowship, Walter B. Nettleton Scholarship, and the William G. Reed Endowed Fellowship in Sustainable Resource Sciences). The Article Processing Charge was funded by University of Washington College of the Environment.

Conflicts of Interest: The authors declare no conflicts of interest. B.D. is a member of the Environmental Chamber on the Forest Stewardship Council-US Board of Directors (an unpaid position). She also serves on the Washington Forest Practices Board which oversees Washington State Forest Practice Regulations. FSC International, FSC-US, and the State of Washington provided no funding and played no role in the design of the study, the collection, analysis, or interpretation of the data, nor in the writing of the manuscript or the decision to publish the results.

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