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# A transition to longer rotations for western Washington forests

## Materials and methods

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### Background & purpose

Resilient Forestry has developed a model to facilitate exploration of forest management options for western Washington forests. A major objective of this model is to understand how policies lengthening rotation ages would affect forest and wood product carbon stocks, timber harvest volumes, and economic returns to the forest products industry.

The purpose of this document is to describe the materials, methods, and assumptions used to create the model. No model is a true representation of reality. In formulating this model, we endeavored to make assumptions and set parameters to reflect a fair representation of the questions under study. This required some simplifications and judgment; these are also described in this document.

### Overview

We implemented the model using a linear programming (LP) approach. We selected LP primarily because it is generally accepted and widely understood as a tool to set sustainable harvest levels and accomplish strategic planning for forest management. For example, LP and similar optimization methods are used by the timber industry, Washington Department of

Natural Resources managing state trust lands, and Bureau of Land Management managing O&C timberlands.

The analysis process began by collecting plot data for the study area and stratifying plots by forest type, site index, age class, and ownership. We modeled growth and yield for each plot under an archetypical silviculture regime and used those model results to calculate yield values for each stratum. These yield values served as coefficients in the LP. LP parameters were set to represent the assumed management situation and LP results were postprocessed to give estimates of a variety of metrics of interest. The model was functionally delivered as a web application with interactive parameters set by the user. The following sections describe this workflow in greater detail.

### Study area and current conditions

We defined the study area to include all of Washington state west of the Cascades crest. We characterized the current conditions of the study area using Forest Inventory and Analysis (FIA) data from the US Forest Service.

We filtered FIA plots to select only plots in state or private ownership (FIA codes 31 and 46). Due to FIA privacy requirements, private ownership includes both small and large/industrial private, as well as tribally-owned forestland. We then filtered FIA plots to select Douglas-fir or western hemlock forest types (FIA codes 201 and 301, respectively), since these represent the majority (65%) of the state- and privately-owned productive forest estate. This simplification kept plot stratification tractable while still maintaining relevance to the large majority of the study landscape. Lastly, we filtered to select only FIA plots that did not have reserve status (RESERVCD = 0) to omit lands that are not legally in a harvest landbase, e.g., state parks. Note that this filter only captures lands that are statutorily barred from commercial timber management, it does not capture lands that are administratively withdrawn - whether temporarily or permanently - from commercial production.

We classified site index for each plot using Douglas-fir trees from the FIA SITETREE table. We dropped from analysis plots that had no recorded site trees. When plots had more than one recorded site tree, we took the average base age corrected site index height. We classified site tree height into site index classes based on the values given in Table 1.

Site index class	Site tree height range (base age 50)	Site tree height range (base age 100)
I	0 - 75 ft	0 - 110 ft
II	75 - 95 ft	110 - 130 ft
III	95 - 115 ft	130 - 165 ft
IV	115 - 135 ft	165 - 195 ft
V	>135 ft	>195 ft

**Management scenarios and growth/yield modeling**

To understand the effects of changing rotation ages on timber volume and carbon outcomes, we defined a basic archetypical management regime, then modeled the application of that regime with varying final harvest ages using the Forest Vegetation Simulator (FVS). The management regime consisted of a clearcut harvest at a given age. All trees less than 9” DBH, including non-merchantable and advance regeneration, were removed, while six trees per acre (TPA) between 9” and 36” DBH were retained. Trees above 36” DBH were not considered merchantable. Making the LP model tractable also required setting a maximum stand age for harvest. We set this to 120 years, since most trees were >36” DBH (and thus too large for most regional milling infrastructure) by that age. All plots were grown up to a starting year of 2025 before further modeling.

In early testing, we explored allowing the LP to select between a thinning regime versus a growth regime with no thinning before final harvest. The LP virtually always selected the thinning regime versus the no-thinning regime, and so we dropped the no-thinning regime for simplicity.

Post-treatment, stands were immediately replanted with 100% Douglas-fir on a 10’ spacing (435 TPA) and an average 85% survival rate. Any stands that reached or exceeded 65 Curtis relative density (RD) were commercially thinned to a residual RD of 30. No thinning occurred when the 65 RD threshold was met within 15 years or fewer from an upcoming final harvest.

We ran scenarios with final harvest ages ranging from 35 years to 120 years. For each plot we repeatedly modeled scenarios spanning two rotations, using every factorial combination of first-entry and second-entry ages between 35 and 120 years in 5-year intervals. In this way, each simulation yielded one instance of harvest results based on actual measured stand conditions, and a second instance of harvest results based on the simulated regenerated

stand. The regenerated stands included a signal of the original measured stand conditions through their inclusion of the 6 TPA retention from the initial harvest. An example of this scheme follows.

Stand age in 2025: 55

Simulation 1: Harvest at age 55, regenerate, harvest at age 35

Simulation 2: Harvest at age 55, regenerate, harvest at age 40

Simulation 3: Harvest at age 55, regenerate, harvest at age 45

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Simulation 18: Harvest at age 55, regenerate, harvest at age 120

Simulation 19: Harvest at age 60, regenerate, harvest at age 35

Simulation 20: Harvest at age 60, regenerate, harvest at age 40

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Simulation 36: Harvest at age 60, regenerate, harvest at age 120

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Simulation 235: Harvest at age 120, regenerate, harvest at age 35

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Simulation 252: Harvest at age 120, regenerate, harvest at age 120

Thus, each plot was simulated for growth modeling up to 324 times (5-year steps 35-120 inclusive = 18 potential harvest ages;  $18^2 = 324$ ) depending on starting age.

For each simulation, we tracked various metrics of interest. From the FVS Summary2 output tables, we recorded net board foot volume (column "RBdFt") from final harvests and commercial thins. From the FVS Carbon table we tracked total standing carbon (above- and below-ground; column "Total\_Stand\_Carbon"). From the FVS Hrv\_Carbon table we tracked amounts of carbon stored in durable wood products (column "Products"). This was not intended to be a carbon lifecycle analysis; we did not account for any other sources/sinks of carbon such as wood in landfills, substitution, or leakage.

## Calculating yield tables

We compiled the FVS results into yield tables giving the amount of each metric of interest yielded at each age class for each stratum. The metrics of interest were net board foot volume harvested, wood product carbon harvested, and total standing forest carbon. The age classes were 5-year bins ranging from [0, 5) through [175, Infinity). We selected 175 as the maximum analysis age since this was the age at which the metrics all plateaued to within 90% of their maximum observed values. The strata were: (1) ownership - state vs. private, (2) site class - I through V, and (3) forest type - Douglas-fir vs. western hemlock, for a total of 20

combinations. Combined with the 36 age classes, this gave 720 yield values for each of the three metrics.

In an initial version, we simply calculated the average value for each metric within each of the 720 yield classes based on the FVS results. However, due to highly imbalanced data among the classes, this resulted in erratic patterns of both positive and negative growth with increasing age class for many strata. This made for an unstable and marginally useful LP. To improve this, we took the average values for board foot harvest volume and fit a cubic spline smoothing curve for each stratum. We selected smoothing parameters between 0.4 and 0.6, basing the amount of smoothing on visual review of the curve fit. Then, we used ordinary linear models to estimate the two carbon metrics as functions of the smoothed board foot volume metrics. Maintaining direct relationships among the three metrics allowed for the LP to have more stable solutions.

## Linear program

We implemented the LP using the lpSolve library within R. The LP was defined with solution variables as the number of acres in each stratum to either harvest or not harvest during each 5-year time period from 2025 to 2095. We defined three possible objective functions for the LP: Max MBF, Max NPV, and Max C. Max MBF maximized the total cut volume over the entire analysis time period by setting the board foot volume yield tables as the coefficients for the LP. Max NPV was based on Max MBF, but expressed in terms of net present value based on user-defined log prices, logging/hauling costs, sale administration costs, reforestation costs, and discount rate. Max C was based on the sum of the forest carbon and wood product carbon yield tables, with the wood product carbon pools decayed over time according to methods given by Hudiburg et al. (2019).

LP constraints included (1) area control, to set the initial distribution of acreages in each stratum, grow the strata over time, constrain harvests to given minimum and maximum stand ages, and reset age classes after harvest, (2) a minimum area-weighted average stand age for the final time period, and (3) harvest continuity, to require maximum period-to-period harvest volume to be constrained by a user-specified percent variation.

## User interface

We harnessed the LP to an interactive user interface to allow many of the key parameters to be varied and experimented with. First, the user can set a curve for the minimum stand harvest age to vary over time. This is the core functionality of the tool: it allows definition of a

transition between minimum rotation ages over time. This transition can be set to occur over any time period and with any shape of curve. The user can also set a maximum stand harvest age that varies over time.

The user can select whether to include state lands, private lands, or both, and can specify the assumed number of acres included in each category. In either case, the initial distribution of acres in each age class and stratum is drawn from FIA data, which is intended to represent an unbiased sample and so should be suitable for this application. When both state and private lands are included, the starting distribution is drawn from FIA datasets for both, represented proportionately with the user-identified acreage values.

The user can select the minimum area-weighted harvest age at the final time period, the allowable harvest volume percent variability between successive 5-year periods, the current annual harvest volume (to initialize the inter-period variability constraint), and the minimum age where commercial thinning is allowed to occur.

Finally, the user can set the economic parameters used to calculate NPV, including average stumpage value for all timber species, average per-acre cost to lay out and administer a timber sale, average per-mbf stump-to-truck cost for timber harvesting, average per-mbf cost to haul timber to a primary manufacturing facility, average per-acre reforestation cost, and the discount rate to use for NPV calculations.

The user can also select between the Max MBF, Max NPV, and Max C objectives.

After solving the LP, the user interface renders various graphs and outputs summary tables for various metrics for each time period.