Plot level comparative Global Warming Mitigation Potential analysis of Red Alder Wood & Douglas fir in the Pacific Northwest

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Abstract

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Working forests help remove CO_2 from the atmosphere, and when the trees from these forests get harvested, some of that sequestered carbon pass on to harvested wood products. Wood products produced from sustainably harvested forests (where average annual harvests are lower than the annual biomass accumulation) could help decrease atmospheric greenhouse gas (GHG) since they store the biogenic carbon removed from the atmosphere. Such processes that help reduce atmospheric GHGs are measured by their global warming mitigation potential (GWMP).

Red Alder (RA) is a species of particular interest as it is known for rapid growth at its early stage compared to conifers. Utilizing Red Alder wood products is expected as one of the natural climate solutions for global warming. Using a temporally dynamic LCA modeling, this study estimates the GWMP of RA wood products over a 100-year (GWMP100) and 25-year (GWMP25) time horizons and compares those with the corresponding GWMPs of the Douglas-Fir. The research also factors in the actual DF and RA site class indices (SIs) of all forestland in Washington.

The GHG calculations and corresponding GWMP estimates factor in a cradle-to-grave analysis of wood products' emissions and storage documentation, starting from plantation to the disposal of wood products. In addition, this research also calculates net present values (NPV) of the first cycle of plantations to understand preferable harvesting ages (HA) to balance economic profitability and contribution to mitigating global warming.

The study result shows that the area where DF produces more GWMP is more extensive than RA under the rotation with industrial-preferred harvesting ages in PNW. The optimal harvesting age to balance NPV and GWMP is 25 years for RA, and 50 years for DF, respectively.

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Chapter 1. INTRODUCTION

Climate change is an urgent problem in the world. Emissions of greenhouse gases (GHG), such as CO_2, CH_4 and N_2O, through human activities have elevated global warming. The concentrations of atmospheric CO_2 reached the highest in 2019 over the past 2 million years.[1] The U.S. government is trying to achieve the goal of a net-zero emissions economy by 2050.[2] Net-zero GHG emissions represent the balance between the amount of anthropogenic GHG generation and anthropogenic GHG sinks, meaning net GHG emissions is zero compensated by sequestering GHG from the atmosphere, keeping them in sink sources. It is expected to discontinue global warming caused by humans, and /or bring a minor retreat from peak warming levels.[1] Therefore, carbon sink is integral for mitigating global warming. Working forests help remove the atmospheric CO2 from the atmosphere, and when the trees from these forests get harvested, some of that sequestered carbon pass on to harvested wood products. Wood products produced from sustainably harvested forests (where average annual harvests are lower than the annual biomass accumulation) could help lower atmospheric GHG since they store the biogenic carbon removed from the atmosphere. In addition, wood products works as substitution of materials with higher GHG emissions through manufacturing processes, such as concrete or steel. Replacing those high-energy consumption materials with wood products leads to decrease the emission of GHGs by the difference in production of those.[3] Increasing opportunities for utilizing wood products means producing more environmental benefits.

The primary industrial softwood tree species in the Pacific Northwest (PNW) is Douglas-fir (Pseudotsuga menziesii), which accounts for the largest share of sawtimber volume on timberland in Oregon State (OR) and Washington State (WA).[4], [5] It is recognized that Douglas-fir has prominent growth, yield, and economic value. [6] On the hardwood side, Red alder (Alnus rubra) is the largest hardwood resource in PNW, the sixth most sawtimber volume on timberland in WA, and the fifth most in OR . [4], [5]Red alder inhibits in PNW Area at less than 1,100 feet elevation from the coast side of Alaska to northern California. It is one of the famous hardwood timber sources in the area. It commonly grows in riparian areas with high tolerance against poor drainage soil. Though Red alder stands can be pure and mixed stands, mixed stands such as with Douglas fir. Its longevity is shorter than Douglas fir but can grow in low-site index soil. One of its notable functions for forest ecology is high nitrogen-fixing, which enables soil to restore site productivity.[7] Besides, Red alder induces organic acids, which enhance mineral weathering. It leads to increased availability of cations and phosphorous, promoting fixing atmospheric nitrogen and growth. Hence, Red alder plays a vital role in successional trees on soils with poor nitrogen or degraded soil by external factors such as disturbances to improve its productivity.[8] In addition, It shows high growth in its height in an early age. Red alder reached almost half of its matured height by 15 ages. The height can be 24 meters at 20 ages on suitable sites. The growth of young Red Alder outstrips those of other conifer associates. While Douglas fir grows 4 meters at 15 ages, Red alder reaches 15 meters at the same age on average sites.[9] Therefore, Red alder can supply timbers with short rotation cycles. Diseases that influence conifers do not affect Red alder. Managing its planting brings possibilities of higher production with better quality in short intervals than natural stands. [10] The significant growth potential of Red alder makes us anticipate that Red alder produces more carbon sink in its wood products than Douglas-fir. Understanding the carbon sink potential of Red alder wood products compared to Douglas-fir is essential to quantify their contribution to the mitigation of global warming, which helps landowners and policymakers make decisions for forest management considering carbon storage benefit.

Estimating the carbon storage benefit brought by wood products requires assessing the life cycle of products to consider the environmental impacts, including GHG emissions caused in the related process. Life cycle assessment (LCA) is an internationally recognized tool to calculate the environmental impacts of products. LCA enables us to quantify the variety of environmental impacts in the entire life cycle of products, which starts from resource extraction via manufacturing products, transportation, and use to the disposal process.[11] The associated process to the system of wood products this study focuses on are planting, harvesting wood, manufacturing products, use, and disposal (landfill, combustion, or recycling). Carbon storage shows temporal changes. The dynamic LCA, which factors time in LCA, is applied to the temporal carbon sequestration.[12], [13]

The environmental benefit of carbon sink removing GHG from the atmosphere are measured by Global Warming Mitigation Potential (GWMP). The Global Warming Potential is time-integrated cumulative Radiative Forcing (RF) owing to a pulse emission of one unit of CO_2. The radiative forcing values, which is a concept to compare different drivers for climate change quantitatively, are adjusted to a unit of CO_2 equivalent, following the code of the Intergovernmental Panel on Climate Change (IPCC). [14], [15] The negative GWP values represent carbon storage credits, while the positive GWP indicates GHG emission credits. The GWMP describes the credits for how GHGs are removed from the atmosphere. Therefore, the positive GWMP equals the negative GWP, and vice versa. The systems that generate the negative GWP values are described as the Global Warming Mitigation system as they sequester carbon and are measured by GWMP. The carbon storage benefit produced in the system of manufacturing wood products from sustainable forest management offsets negative impacts caused by the processes of harvesting, manufacturing, transportation, and disposal. The system of wood products brings net negative GWP, resulting in its benefits is measured by GWMP.

Ganguly et al. (2020) calculate the global warming potential of wood products manufactured with logs harvested from Washington state's private forest land. That study used cumulative radiative forcing with 100 years time horizon following IPCC's rule related to it to measure the impact of carbon sequestration by wood products and GHG emissions during harvesting and manufacturing products. The total global warming potential of wood products in 2015 from private forests in Washington state is - 1,735,990 t CO2eq incorporating GHG emissions, that is based on the radiative forcing concept.[16] However, it is unclear how much environmental benefit Red Alder products can bring for the long-term (i.e., 50 years, 100 years) as a climate change solution.

The economic profitability of plantations is a vital driver for manufacturing wood products using logs harvested there. Net present value analysis is a regular method to evaluate the economic value of the plantation systems. Atkinson et al. (1979) estimated present net worth, which is the same concept as NPV, for Douglas-fir and Red Alder crop rotations in six management scenarios. It suggested that incorporating Red alder in the cropping system can produce profit based on the cost and price at that time. Diaz et al. (2018) used the net present value as one of the indicators to understand tradeoff relationships among timber yield, discounted cash flow, and carbon storage over 100 years by comparing four management scenarios for Douglas-fir. Its result demonstrated that the forest practices that increase carbon storage greater than a regular practice for Douglas-fir lead to a decline in financial viability.[17] This study calculates NPV on each plantation of Red alder and Douglas-fir to suggest a practical management method with better GWMP generation without losing economic feasibility.

Chapter 2. ANALYSIS METHOD

2.1 RESEARCH QUESTIONS AND OBJECTIVES

2.1.1 *Research questions*

This study addresses the questions below.

- How much does Red alder contribute to mitigating Global Warming as a natural climate solution (NCS) compared to Douglas-fir, a dominant industrial tree species in PNW?
- How can we enhance the contribution of Red alder to mitigating global warming?
- What is the optimal management of plantations to produce GWMP considering the profitability of forestry?

2.1.2 *Research objectives*

The aims of this research to attain answers to the research questions are

- Modeling the plot-level lifecycle of Red alder and Douglas-fir from planting a plantation to the disposal of wood products manufactured from those woods.
- Estimating carbon sequestration provided during the Red alder and Douglas-fir lifecycle with 25-year and 100-year time horizons.
- Estimating global warming mitigation potential (GWMP) provided during the Red alder and Douglas-fir lifecycle using dynamic life cycle assessment with 25-year and 100-year time horizons.
- Finding opportunities to increase GWMP of Red alder by deepening understanding of its characteristics varied by different conditions of plantations.

- Estimating Net Present Value (NPV) to investigate the economic feasibility of plantations in each condition.
- Detecting optimal harvesting age balancing GWMP and NPV.

2.2 ASSUMPTIONS

The cumulative RF is a pulse emission of one metric ton of CO_2 (t CO_2) integrated from the beginning of the time horizon until the last year of sequestration or the end of the evaluation period. It can be used as a measurement to evaluate carbon sequestration in wood products.[17] The functional lifetime is used to estimate the global warming mitigation potential of wood products considering the remaining carbon in products each year after manufacturing. GHG emissions during harvesting and manufacturing are also estimated by using the same RF concept, where the time for which t CO_2 is integrated is over 100 years.

The time horizon of this analysis is 25 and 100 years following the IPCC's code about GHGs pulse emissions decay rate in the atmosphere and RF concepts. This study focuses on the cumulative global warming mitigation potential obtained by repeating the cycle of manufacturing forest products with logs harvested at the same forest stand. Therefore, the harvesting age can be one of the integral factors in the results of this study. This analysis adopts the harvesting age ranging from 20 to 40 years for Red alder and from 20 to 55 years for Douglas fir, considering the typical rotation age and comparing both species. In addition, the differences in conditions in the plantation, such as site index, tree density, and treatment, influence the estimation significantly. Hence, this study calculates 378 Red alder and 324 cases of Douglas fir to investigate the effect of the difference in plantation conditions. (Table 1)

Table 1. Conditions for plantations

Species	Red alder	Douglas-fir
Site Index (ft)	35, 45, 55, 65, 75, 85	85, 95, 105, 115, 125, 135, 145, 155, 165
Harvesting age (year)	20 - 40	20 - 55
Density (tree/acre)	High (550), Low (225)	435
Treatment	No treatment, Thinning (only in high density)	No treatment

Note: The site index for Red alder is its height (unit: ft) at the age of 20 years, that of Douglas-fir is its height (ft) at the age of 50 years.

Carbon Neutrality: This study assumes that the amount of carbon stocked in the wood products during their functional lifetime until disposal is the same volume as the corresponding carbon emissions of CO2 for the same term from the atmosphere.

Wood product mix: This study uses the results of the Red alder Mills survey conducted by CINTRAFOR (2022) to create the Red alder wood product mix. [18] This research assumes that wood products mix as representative data for Red alder wood products in Washington and Oregon State. Considering Douglas-fir, this study estimates its product mix based on Ganguly et al.(2020) and the Washington Mill Survey of 2016 published by the Washington Department of Natural Resources (DNR) as a representative wood products mix in Washington and Oregon.[16], [19] We consider the category of Miscellaneous products as particleboard in the created product mix for every specie. Furthermore, this study assumes that the logs produced in Washington and Oregon and processed out of the two states are under the same product manufacturing mix as Red alder and Douglas-fir.

The stand development prediction: This study uses CIPSANON and ORGANON as simulation tools to estimate the log volume produced at the specific plantation ages of Red alder and Douglas-fir.[20] The model in the tools considers early plantation mortality and suppression-based mortality that happened by exceeding the capacity of trees but not episodic mortality caused by disturbances such as wildfires and severe storms. This research also assumes the forest growth rate in each plantation does not change over the evaluation period (100 years). In addition, this paper assumes that no land changes from industrial plantations to other lands not for forestry happen.

The end-of-life scenario: All durable wood products (softwood lumber, hardwood lumber, plywood, and pallet) after their first lifetime are processed in the same percentage of management pathways in 2018 provided by the U.S. Environmental Protection Agency.[21] Estimating global warming potential during the processing of wood products adopts GHGs emission values of dimensional lumber and Medium density fiberboard. In addition, this study assumes that all recycled wood products after their second functional lifetime are disposed of in landfill sites or by combustion.

The Functional life of wood products: This study assumes that durable wood products are recycled into Miscellaneous products once and used until the end of their second functional lifetime. Considering paper, this study assumes it is recycled once after its first functional lifetime and discarded after its second functional lifetime.

2.3 PLANTATION DEVELOPMENT MODEL

2.3.1 *Forest stands development of Red alder and Douglas-fir*

This study estimates the global warming mitigation potential per acre of plantation forest. The volume per acre at a harvesting age in Red alder and Douglas- fir is necessary for the beginning of the calculation. Simulation data estimated by the CINPSANON and ORGANON is used in this study. They are growth and yield model programs managed by the Center for Intensive Planted-forest Silviculture. CIPSANON is designed to predict future stands development for managed Douglas -fir or western-hemlock plantations managing in western Oregon, Washington, and southwestern British Columbia to predict annual tree growth and mortality. ORGANON incorporates two versions, two variants of the southwestern Oregon version of ORGANON (SWO-ORGANON) and those elements of the Stand Management Cooperative version of ORGANON (SMC-ORGANON). SWO-ORGANON is designed for southwest Oregon's mixed species forests stands. In contrast, SMC-ORGANON is for the young-growth, Douglas-fir, and western hemlock stands, singularly or in combination, of southwest British Columbia, western Washington, and northwest Oregon. They are essential for predicting non-Douglas fir and western hemlock species within CIPSANON.[20]

The Red alder stands data input in the program from Hardwood Silviculture Cooperative (HSC), a multi-faceted research and education program dealing with Red Alderalder and mixed stands of Red alder and Douglas-fir. Its objective is to improve understanding of how stand density management affects Red alder growth, yield, and wood quality and to develop the Red alder growth and yield model.[22] The program researches 26 variable-density plantations from Coos Bay, Oregon, to Vancouver Island, British Columbia.[23] The Red alder plantation model was first installed in ORGANON in 2011 based on the data collected by Weyerhaeuser and HSC plantations. However, those two datasets adversely influence some equations in the model, refitting the model based on the updated datasets of HSC plantations implemented from 2017. The Red alder stands used in HSC research are divided into three types. Type 1 is a natural stand with thinning treatment. Type 2 is a variable-density Red Alder plantation with several thinning and pruning treatments. Type 3 is a mixed plantation with Red alder and Douglas-fir. 25 Type plantations and 7 Type 3 plantations were used in refitting the model. [24]

The conditions of the harvesting log in both simulations is indicated in Table 2. This study uses conversion factors shown in Table 3 to calculate the ratio of merchantable log volume to total aboveground biomass volume with the simulation data. [25]

Table 2. Log specification of the model

	Red alder	Douglas-fir
Log length (ft)	30	40
Minimum log length (ft)	10	16
Minimum top diameter (inches)	5	8

This study focuses on the first functional life of products from seeding to the end of use. The premise of the dynamic LCA is that the amount of CO_2 stored in the alder products for their lifespan is equal to excluding the corresponding amount of CO_2 emission from the atmosphere for the same term. Modeling how red-alder wood products are used is based on the aboveground biomass, timber harvest rate, and state's wood products mix. As a leading data source, this uses LCA data of the supply chain of alder products in Washington state conducted by CINTRAFOR.

Table 3. Conversion factor

Log diameter (inch)	Board ft per cubic ft
6	3.32
8	3.41
10	3.96
12	4.52
14	5
16	5.41
18	5.75
20	6.03
22	6.26
24	6.45

source: Oester et al.(2009)

2.3.2 *Estimation of biomass in the forest stands of Red alder and Douglas-fir*

It should be noted that this study uses equations based on a combination of diameter and height for wood and bark biomass calculations and uses equations based on only diameter for foliage and branch biomass calculations because the parameters of $\beta_{foliage3}$ and $\beta_{branches3}$ for Red alder are not indicated in the article as those p-values are less than 0.5. Just CIPSANON and ORGANON calculate the Douglas fir biomass at each age without any other model in this study. Figure 1 shows the biomass growth of both species simulated by the model. Site Index:65 in Red alder forest and Site Index:95 in Douglas fir forest are considered normal site productivity for each species.[9], [26] The figure shows that the cumulative biomass of Red alder still outstrips that of Douglas fir at the age of 40 years. Since the unit of estimated biomass is imperial tons per acre, this study adopts 0.50 as a conversion factor to convert the biomass into carbon equivalents (imperial tons Ceq per acre) , and this study also uses a stoichiometric conversion factor of 3.67 to convert the quantity of carbon into the equivalent amount of carbon dioxide (CO_2) (imperial tons CO_2 per acre).[27]

Equation 1. Estimation of Biomass with diameter and height

$$y_{wood} = \beta_{wood1} D^{\beta_{wood2}} H^{\beta_{wood3}} + e_{wood}$$

$$y_{bark} = \beta_{bark} \; D^{\beta_{bark2}} H^{\beta_{bark}} \; + e_{bark}$$

$$y_{foliage} = \beta_{foliage1} D^{\beta_{foliage2}} + e_{foliage}$$

$$y_{branches} = \beta_{branches1} D^{\beta_{branches2}} + e_{branches}$$

$$y_{stem} = \hat{y}_{wood} + \hat{y}_{bark} + e_{stem}$$

$$y_{crown} = \hat{y}_{foliage} + \hat{y}_{branches} + e_{crown}$$

$$y_{total} = \hat{y}_{wood} + \hat{y}_{bark} + \hat{y}_{foliage} + \hat{y}_{branches} + e_{total}$$

Where y_i is the dry mass of component i (wood, bark, foliage, or branches, in kg), $\hat{y}_{wood}$ is the modeled value of y_i, D is tree DBH (cm), H is total tree height (m), β_{ik} is the parameters to be estimated (i is as above, k = 1, 2, or 3), and e_i is the error term for component i. β_{wood1}=0.0051, β_{wood2} =1.0697, β_{wood} =2.2748, β_{bark1} = 0.0009, β_{bark2} =1.3061, β_{bark3} =2.0109, $\beta_{branches1}$=0.0131, $\beta_{branches2}$=2.5760, $\beta_{foliage1}$=0.0224, $\beta_{foliage2}$=1.8368.[28]

2.3.3 *Estimation of forest residue*

The amount of wood biomass left on the plantation after harvesting works as a carbon storage. However, the forest residue decays releasing its carbon as time goes. Therefore, considering decay rates for those is necessary to estimate global warming potential. In this study, the forest residue is assumed of the sum of branches, foliage, wood, and bark. The wood in the forest residue is calculated by subtracting collected logs from the original wood biomass. This research assumes that half of no-merchantable biomass is left on the ground after harvesting as forest residues and half is burned as slash piles. According to the decomposition model indicated by Olson (1963) , the forest residue that remained in the forest at each time *t* is expressed in Equation 2.[29]

Equation 2. Estimation of forest residue

$$E_{forest\ residue,CO_2}(t) = -X_0 e^{-mt} \tag{1}$$

, where X_t represents decomposed forest residue at time t, X_0 represents the original amount of forest residue at the beginning, and m represents a decay rate, m = 0.152. Emissions from forest residue is considered as biogenic carbon emissions. Hence, those are not counted into estimates of the global warming potential.

2.4 WOOD PRODUCTS MODEL

2.4.1 *Creation of wood product mix*

The wood product mix is a significant deciding factor in estimating this study's CS and GWMP of wood products. It shows how Red alder and Douglas fir logs are distributed to manufacture different forest products, such as lumber, plywood, and chips. Each product's environmental impact differs substantially depending on the manufacturing process and its use in an economy. Therefore, the product mix influences the GWMP. The creation of the Red alder product mix is based on collected data from a report conducted by the Center for International Trade in Forest Products (CINTRAFOR). The report focuses on the LCA of Red alder lumber manufactured in Washington and Oregon—mills. CINTRAFOR obtained the production amounts of forest products. It can be converted into the product mix by adjusting units of numbers. Figure 1 indicates the product mix created by the report. It shows that the biggest share of Red alder logs is used for Chips. This research uses a product mix estimated by Ganguly et al.(2020) for a Douglas fir product mix (Figure 2, Ganguly et al., 2020). [16]

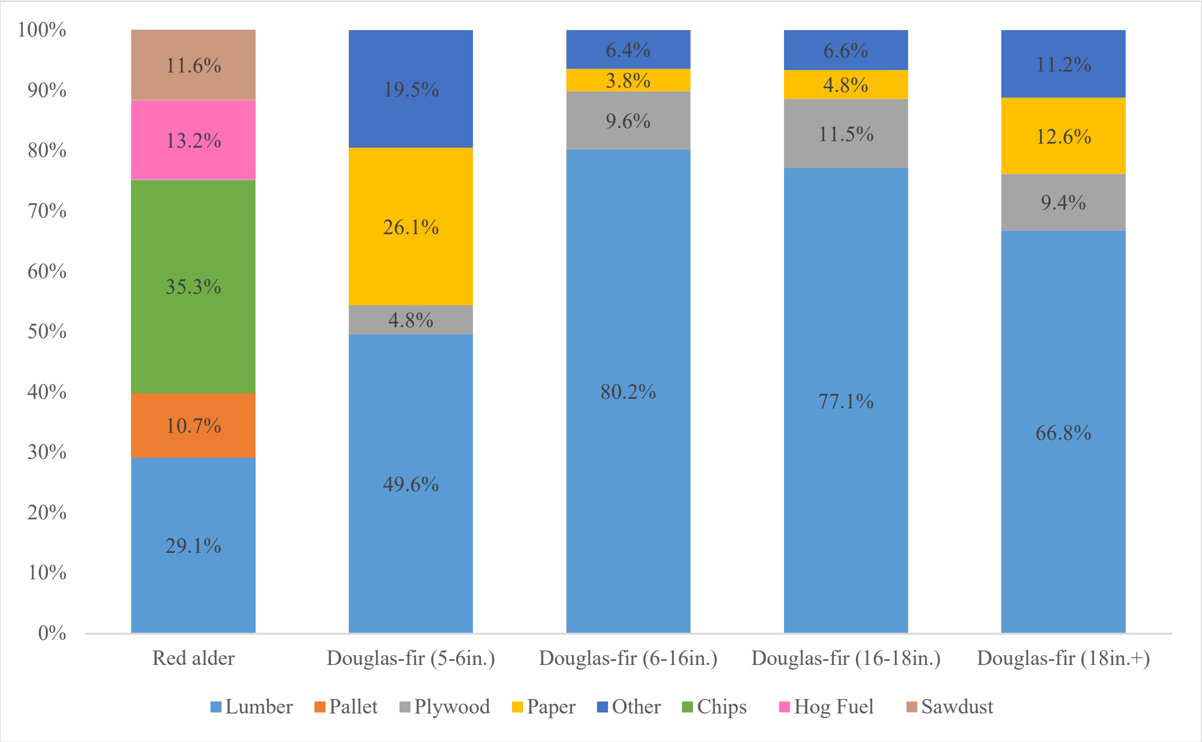


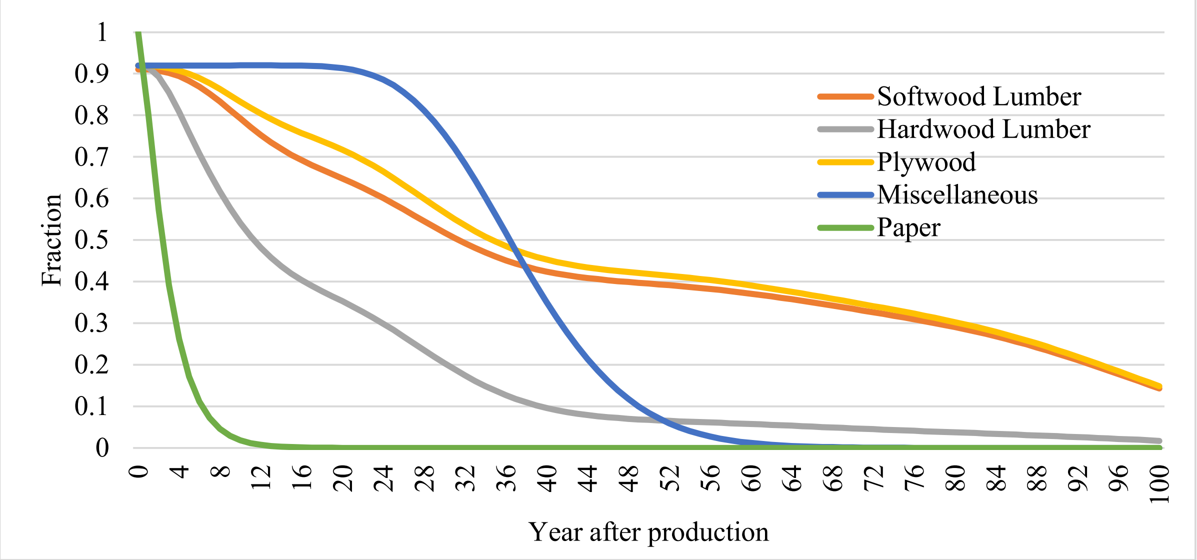
Figure 1. Product Mix of Red alder and Douglas fir

Source: The Red Alder wood product mix is estimated by the data from CINTRAFOR(2020). The product mix of Douglas-fir is calculated using "table 12 Log consumption – by diameter in inches" in Washington Mill Survey 2016.[8] The categories of shake & single, and log export are excluded.

in each diameter class. The product mix by diameter classes for Douglas fir is estimated by the Washington mill survey[19], with the assumption of the groups of diameter classes based on some field experiences. It indicates that logs with diameters 5 to 6 inches are consumed more for manufacturing paper and other rather than other classes. Other means miscellaneous products, which this research assumes particleboard. The diameter group with 6 to 16 inches has the highest ratio for lumber of four, while the diameter size is the second smallest. Though the class of 16 to 18 inches has a similar tendency as the former class, the class of more than 18 inches increases the share of paper and the other around two times bigger than the one class below. Lumber occupies the largest part of every class. As each diameter class has different characteristics for manufacturing wood products, the product mix grouped by diameter leads to a more accurate estimation of results in this study.

2.4.2 *Wood products functional lifetime*

The functional lifetime that represents how long products are used after manufacturing can vary depending on the type of wood products. Lifetime is integral since it substantially affects the result of the GWMP. Ganguly et al. (2020) adopt the data of the "Fraction of Carbon Primary Wood Products Remaining in End Use up to 100 Years After Production" cited from the U.S. Department of Agriculture Report. (Table 6-A-2 in Hoover et al.)[16], [31] This study uses the updated value reported by the same organization to show the data between 0 years and 100 years.[32] The data includes a fraction of carbon in Softwood lumber, Hardwood lumber, Softwood Plywood, Oriented Strand Board, Non-Structural Panels, Miscellaneous Products, and Paper. According to the survey by CINTRAFOR (2022), Red alder logs are used for manufacturing lumber, pallet, chips, hog fuel, and sawdust. Therefore, this study used Hardwood lumber, Miscellaneous, and paper products for pallets, chips, hog fuel, and sawdust in Red alder estimation. Based on the produced type of products indicated in the Washington Mill survey by DNR, this study also used softwood Lumber, softwood plywood, particle board, and paper in the data to estimate the global warming potential for wood products manufactured in Washington and Oregon. Each half of the lifetime based on the data is 31 years in softwood lumber and plywood, 11 years in hardwood lumber, 34 years in plywood, 36 years in Miscellaneous products, and two years in paper. The updated fraction value shows a much faster decrease of carbon in hardwood lumber, compared to half of the lifetime of hardwood lumber is 34 years in the previous report. (Table 6-A-2 in Hover et al.(2014)) [19] This research assumes that the primary products in US national market are used in the same percentage of end-use all over the country, exported primary products as well. Our analysis compares RF results with the average fraction of carbon over 100 years provided by the report. This analysis assumes that carbon storage exists from the beginning of the evaluation point (time = 0), which means the year of the harvesting, until the end of their functional lifetime since this study focuses on the global warming potential of wood products.



Source: Murray et al. (2023)

Figure 2. Fraction of Carbon in primary Wood Products for 100 years

(year 0 shows fraction at time of production)

2.4.3 *Estimation of emission profiles*

The objective emission for evaluation is cradle-to-grave fossil emissions, including those released during harvest, transportation, manufacturing, disposal, and recycling. This study mainly uses U.S. Life Cycle Inventory (US LCI) data and the data incorporating the mills survey in CINTRAFOR(2022) with the mills survey implemented in this study for greenhouse gas emissions value. [18] Considering paper in Douglas fir wood products, this research assumes it is a mix of freesheet, coated and uncoated, and mechanical, coated and uncoated. In addition, the average emission value taken from the US LCI database is used in this analysis.

Table 4. Life cycle Inventory for the Red Alder wood products greenhouse gas (CO2 and CH4) emission values in this analysis

Wood products	Life cycle inventory (LCI)	Data Source
Lumber, Pallet, Chips, Hog fuel, Sawdust	Hardwood logs	Mills Survey
	Electricity, medium voltage {WECC, US only} market for | Cut-off, U	Ecoinvent 3
	LPG production and combustion, at industrial boiler / US U	US-EI 2.2
	Diesel, combustion, at industrial boiler NREL / US U	US-EI 2.2
	Nature gas, combusted in industrial boiler/US	USLCI
	Wood Combusted, at boiler, at mill, kg, PNW/ US	Mills Survey

Table 5. Life cycle Inventory for the Douglas-fir wood products greenhouse gas (CO2 and CH4) emission values in this analysis

Wood products	Life cycle inventory (LCI)	Data Source
Lumber	Sawn lumber, softwood rough, klin-dried, at klin, m3/PNW_US	USLCI
Plywood	Plywood, at plywood plant, US PNW/kg/US	USLCI
Paper	Paper, freesheet, coated, average production, at mill/kg/RNA	USLCI
	Paper, freesheet, uncoated, average production, at mill/kg/RNA	USLCI
	Paper, mechanical, coated, average production, at mill/kg/RNA	USLCI
	Paper, mechanical, coated, average production, at mill/kg/RNA	USLCI
Miscellaneous	Particleboard, average softwood, particleboard mill/m3/RNA	USLCI

US LCI data of wood products and the LCI data obtained by the mills survey show that the sum of CO_2 and CH_4 emissions occupies more than 98% of the GHG emissions from wood products. Therefore, this study assumes that CO_2 and CH_4 emissions only contribute to estimating emissions through the process from harvesting logs to manufacturing wood products.

The evaluation of emissions adopts the 100-year time horizon. Table 6 shows the value of emissions per product. The manufacturing emissions are considered pulse emissions emitted immediately within the harvesting year (time=0).[16]

Table 6. Emission profiles

Specie		CO_2 emission	CH_4 emission	Unit
Red alder				
	Lumber	0.0755	0.0002	kg / kg of lumber
	Pallet	0.0757	0.0002	kg / kg of pallet
	Other (Particleboard)	0.4286	0.0017	kg / kg of particleboard
	Paper	1.2490	0.0035	kg / kg of paper
Douglas-fir				
	Lumber	0.0912	0.0003	kg / kg of lumber
	Plywood	0.3800	0.0010	kg / kg of plywood
	Other (Particleboard)	0.4602	0.0018	kg / kg of particleboard
	Paper	1.2770	0.0029	kg / kg of paper

2.4.4 *Estimation of landfill*

This research adopts the Waste Reduction Model (WARM) provided by the US Environmental Protection Agency (EPA) to estimate the impacts of wood products processed after their first functional lifetime. Considering the landfill in calculating the global warming potential requires four factors, an initial carbon in the landfill, an emission as CH_4, an emission as CO_2, and a remained carbon in the landfill.[33] In 2018, wood in municipal solid waste such as furniture, pallet, and durable

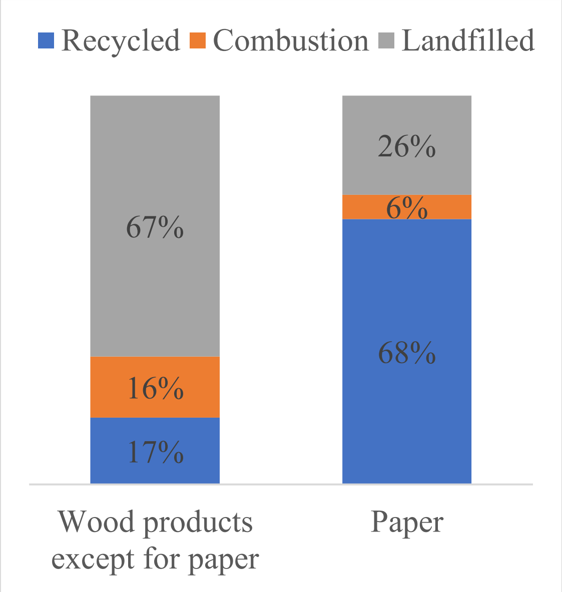


Figure 3.GWP of Red alder (High density, no treatment) in the case of multiple cycles with 100-year time-horizon

products was recycled 3,100 (17%) thousand short tons, was disposed of to use as energy 2,840 (16%) thousand short tons, and was landfilled 12,150 (67%) thousands of U.S. tons. [21]

This study assumes that all durable products (hardwood lumber, softwood lumber, plywood, pallet) are discarded after their first functional lifetime, similar to the same percentage in 2018. Decaying in landfills is a significant factor in considering the emissions and the remaining carbon. The decay function is the same as the equation (1). This research assumes GHG emission values related to the end of life of DF lumber, RA lumber, plywood, and pallet are equal to those of dimensional lumber, and those of particleboard are equal to medium-density fiberboard (MDF) in the WARM model. Regarding paper, paper products in this analysis are assumed mixed paper (general), consisting of 48% corrugated containers, 8% magazines/third-class mail, 24% newspaper, and 20% office paper. This study adopts 0.12 for the decay rate (m), a rate for Dimensional lumber in the wet condition indicated by WARM.[33] Since western WA is an area with rain. According to Wang et al. (2011), the initial biogenic carbon content in dimensional lumber is 49% of dry matter.[34] WARM model considers a 1% adjusted yield of CH_4 as a proportion of dimensional lumber's initial carbon storage, 1% for that of MDF. It also consides 88% adjusted carbon storage as a proportion of dimensional lumber's initial carbon and 84% for MDF. It means that 1% of the initial carbon is emitted as CH_4, and 88% of the initial carbon stays at the landfill of dimensional lumber eternally. Regarding paper, WARM does not indicate those percentages of mixed paper (general). This study estimates those using values of each paper product type weighted by those constitution ratios. The calculated number is 22% for the adjusted yields of CH_4, and 49% for the adjusted carbon storage. [33] Therefore, this study assumes that the initial carbon decays along with the decay function (Equation (1)) until it reaches the certain percentage, 88% in the dimensional lumber case, of its original amount, and the carbon storage is stable after that.

The carbon storage is represented in Equation 3.

Equation 3. Emission of CO_2 in landfill

$$E_{landfill,CO_2}(t) = (1 - CE_j) \cdot e^{-mt}$$

, where m is the decay rate (m = 0.12), and CSE_j is the percentage of the adjusted carbon storage to initial amount of product type j.

The emissions of CH_4 released from the landfill are expressed by Equation 4.

Equation 4. Emission of CH_4 in landfill

$$E_{landfill,CH_4}(t) = -m \cdot ME_j{}^{-mt}$$

, where m is the decay rate (m = 0.11), and ME_j is quoted from the percentage of yield CH_4 toward the initial carbon content in product type j.[35] The landfilling process also releases environmental impacts caused such as transportation. WARM provides those impacts in emission values with a unit metric ton (MT) CO_2eq per short ton. Emission in the transportation of products to landfill sites is 0.02 MT CO_2eq per short ton, equaling 0.022 kg CO_2e per kg. This value is the same in the case of dimensional lumber, MDF, and mixed paper (general). It is also used in the estimation of emissions in the landfill process.

2.4.5 *Estimation of recycling*

This study assumes that 17% of durable wood products are recycled soon after their functional lifetime and 68% of paper as well, as stated above. In addition, all recycled wood products are assumed to contribute to manufacturing particleboards in this study. WARM provides the environmental impact values of reusing dimensional lumber and manufacturing with virgin inputs, assuming that the reuse process is under the recycling management pathways since dimensional lumber is commonly reused. [33] This difference in impacts values between virgin inputs and resued inputs, which is 0.13 MT CO_2eq / Short ton, can be considered to include the impacts that happen in producing viring materials but not in reused materials, such as emissions of harvesting logs, transporting logs from forests to mills, and drying delivered logs. This study assumes that the difference in emissions between particleboard manufacture with virgin material and particleboard manufacture with recycled materials is the same as the gap indicated in the WARM model for dimensional lumber. Therefore, this research uses the emissions of manufacturing particleboards in Table 6 minus the gap, 0.13 MT CO_2eq / short ton, as emissions of recycling durable wood products. The value of the gap is assumed that consists of CO_2 emission. Therefore, the CH_4 emissions from recycling durable wood products are the same as the particleboard production with virgin inputs.

Table 7. Emissions of recycling durable wood products (Unit: kg/kg of particleboard)

Species	CO2 emission	CH4 emission
Red alder	0.3283	0.0017
Douglas-fir	0.3599	0.0018

Regarding emissions of recycling paper, this study uses the emission value of mixed paper (general) production with recycled inputs, 1.09 MT CO_2eq / short ton, which is associated with transportation and process.

2.4.6 *Estimation of combustion*

This study assumes that 16% of durable wood products are combusted after the end of their functional lifetime. Combustion wood products create emissions of N_2O and biogenic CO_2. However, biogenic CO_2 emissions are not considered because of their neutrality. WARM indicates 0.01 MT CO_2 eq per short ton for the transportation to combustion facilities and 0.04 MT CO_2 eq per short ton for N_2O emissions from the combustion for dimensional lumber, MDF, and mixed paper (general) cases.[33] They are equivalent to 0.011 kg CO_2eq per kg and 0.044 kg CO_2eq per kg, respectively. This research uses these values to estimate emissions in the combustion process. Considering the emission created by burning hog fuels, this study adopts the life cycle assessment data of wood-boiler from the Consortium for Research Renewable Industrial Material and assumes that hog fuel is combusted in the same year of its production. CO_2 and CH_4 comprise of the emission mainly. As a result of the calculations based on the LCA data and the Red alder LCA data, Red alder emits 0.159 kg CO_2 and 0.0004 kg CH_4 per kg of hog fuel, respectively. The emissions for Douglas-fir are 0.1108 kg CO_2/kg of hog fuel and 0.0003 kg CH_4/kg of hog fuel.

2.5 ESTIMATION OF GLOBAL WARMING MITIGATION POTENTIAL WITH THE CONCEPT OF RADIATIVE FORCING

2.5.1 *Decay Function of Greenhouse Gases in the Atmosphere*

Each GHG emission's impact on global warming differs depending on their influence estimated by the RF concept. The relative abundance of each GHG in the atmosphere and the radiative efficiency (RE) are the determining factors of it. The measurement of the relative abundance of GHGs in the atmosphere is the decay function that represents the period for which GHG stay in the atmosphere after emitting. That period varies depending on the environmental capacity to transform or exclude those from the atmosphere. The GHG residence time in the atmosphere determines the environmental capacity and its bulk concentration. Based on IPCC's fifth assessment report, the decay of a pulse emission of CO_2 at time t is given by Equation 5.

Equation 5. Decay function of CO_2

$$C_{CO_2}(t) = a_0 + \sum\nolimits_k a_k e^{-t/\tau_k}$$

$$a_0 = 0.2173;\ a_1 = 0.2240;\ a_2 = 0.2824;\ a_3 = 0.2763.$$

$$\tau_1 = 394.4\,years;\ \tau_2 = 36.54\,years;\ \tau_3 = 4.304\,years.$$

The decay of a pulse emission of other GHG at time t is given by Equation 6.

Equation 6. Decay function of GHGs except for CO_2

$$C_{GHG_i}(t) = e^{-\frac{t}{\tau_i}}$$

τ_i = lifetime of the GHG i. [14]According to the updated values of GHG lifetime in IPCC's sixth assessment report, τ_{CH_4}= 11.8 years, and τ_{NO_2}= 109 years.[36]

2.5.2 *Estimating the Radiative Efficiency*

The radiative efficiency is the RF_i per unit mass increase in the atmospheric abundance of species *i* (8.SM.11.1, Chapter 8, Supplemental material, IPCC's fifth assessment report[14]). Multiplying the radiative efficiency with the fraction of species *i* remaining in the atmosphere after the pulse emission, R_i ,provides the radiative forcing, RF_i. This research needs convert the value of the RE provided by IPCC's sixth assessment report from per billion by volume (ppbv) to per kg in order to calculate the RF later. Conversion is made by multiplying the $(M_A/M_i)(10^9/T_M)$, where M_A is the mean molecular weight of air (28.97 kg $kmol^{-1}$), M_i is the molecular weight of species *i* (CO_2;

44.01 kg kmol^{-1}, CH_4; 16.043 kg kmol^{-1}, N_2O; 44.013 kg kmol^{-1}), and T_M is the total mass of the atmosphere, 5.1352×10^{18} kg. [37] The RE value based on the IPCC's sixth assessment report is $1.33 \times 10^{-5}\, W\, m^{-2}\, ppb^{-1}$ for CO_2, $5.7\ \times 10^{-4}\, W\, m^{-2}\, ppb^{-1}$ for CH_4, $2.8 \times 10^{-3}\, W\, m^{-2}\, ppb^{-1}$ for N_2O, which are values including chemical adjustments to incorporate indirect effects of methane and nitrous oxide (Table 7.SM.6, Chapter 7, Supplemental material, IPCC's sixth assessment report[36], Table 7.15, Chapter 7, IPCC's sixth assessment report[38]). As a result, the RE values are $1.70487 \times 10^{-15}\, W\, m^{-2}\, kg^{-1}$ for CO_2, $2.004382 \times 10^{-13}\, W\, m^{-2}\, kg^{-1}$ for CH_4, and $3.588956 \times 10^{-13}\, W\, m^{-2}\, kg^{-1}$ for N_2O.

2.5.3 *Estimating the Radiative Efficiency for a Pulse of Greenhouse Gas*

The RF for a pulse emission of GHG is calculated by multiplying the RE values for the GHG with the decay function for a pulse emission of the GHG at time *t*. Thus, the equation is Equation 7.

Equation 7. Radiative Forcing

$$RF_{GHG_i}(t) = RE_{GHG_i} \cdot C_{GHG_i}(t)$$

Emissions are represented in positive RF values, and the sequestrated carbon dioxide is represented as negative RF values. In this analysis, CO_2 and CH_4 are considered greenhouse gases. Hence, two RFs for those are calculated (i = CO_2 and CH_4).

2.5.4 *Estimating the Emission Profile Vectors*

Applying the RF analysis to the emission profiles requires defining a vector for each emission or removal source *j* and each greenhouse gas *i* (emission profile vector). Therefore, the vector is represented in Equation 8. This study mainly uses eight categorized vectors : four CS (forest stands, forest residue, wood products, landfill) and four emissions (manufacturing products, landfilling, recycling, combustion). Considering the CS for wood products, the vectors consist of the CO_2 values corresponding to the fractions of carbon in primary wood products remaining in their end uses from the manufacturing year *i* to year n, where n is the last year of the evaluation period (i.e., n =24, or 99 in this study), are the vector elements. Considering the manufacturing emissions, the life-cycle-based fossil GHG emissions from manufacturing wood products are the vector elements. This research assumes that all emissions happen at the beginning of manufacturing. The dimension of all vectors equals 100 since it is equivalent to the number of years of evaluation.[16]

Equation 8. Emission profiles

$$E_{j,GHG_i}(t) = \left(e_j(t_1)e_j(t_2) \cdots\cdots e_j(t_{n-1})e_j(t_n)\right)$$

2.5.5 *Calculation of the cumulative Radiative Forcing by the Emission Profiles*

To estimate cumulative radiative forcing (CRF) for the source *j* and GHG_i, each emission profile is multiplied by the RF of the corresponding greenhouse gas unit pulse. The equation is Equation 9.

Equation 9. Cumulative Radiative Forcing

$$CRF_{j,GHG_i} = E_{j,GHG_i}(t) \cdot RF_{GHG_i}(t) = \left(e_j(t_1)e_j(t_2) \cdots\cdots e_j(t_{n-1})e_j(t_n)\right)\begin{pmatrix} RF_{GHG_i}(t_1) \\ RF_{GHG_i}(t_2) \\ \cdots\cdots \\ RF_{GHG_i}(t_{n-1}) \\ RF_{GHG_i}(t_n) \end{pmatrix}$$

The unit of the radiative efficiencies is $W\ m^{-2}\ kg^{-1}$. Hence, the emission profile should be represented in a unit of kg of greenhouse gas. The total of each cumulative radiative forcing for GHG species and GHG emissions/removal source is estimated for the two types of contribution: CS and manufacturing emissions (CO_2, CH_4, N_2O). Equation 10 is for $CRF_j(t)$ that represents CRF for the source *j* at time *t*.

Equation 10. Summing all GHG's CRF at each source

$$CRF_j(t) = \sum_i CRF_{j,GHG_i}(t)$$

2.5.6 *Estimation of the Net Cumulative Radiative Forcing*

The net cumulative forcing measures the impact of the woody biomass system's biogenic carbon emissions and sequestration on global warming. It is calculated by adding up the cumulative forcings of each source *j*. The equation is Equation 11.

Equation 11. Net Cumulative Radiative Forcing

$$NCRF = \sum_j CRF_j(t)$$

To illustrate the shift of the cumulative radiative forcing along the time in a graph, this analysis converts the cumulative radiative forcing for CH_4 into the unit of CO_2eq by multiplying the ratio of the radiative efficiency of CH_4 by that of CO_2. As for the N_2O released by the combustion of products, the emission value is provided in the unit of CO_2eq. Therefore, this study does not have to adopt it.

2.5.7 *Estimation of the Global warming mitigation potential*

GWMP is the time-integrated RF of a pulse emission of a GHG relative to that of a pulse emission of CO2. The IPCC's sixth assessment report provides the values of GWMP for all GHGs (Table 7.SM.6, Chapter 7, Supplemental material, IPCC's sixth assessment report[36]). The GWMP for wood products is estimated as a relative value by dividing the net cumulative radiative forcing at 100 years by the cumulative radiative forcing of CO_2 at the same time. The equation is Equation 12.

Equation 12. Global Warming Mitigation Potential

$$GWMP = \frac{\sum_j CRF_j(t)}{\sum CRF_{CO_2}(t)}$$

All calculations are conducted in R v 4.2.2, a free software, language, and environment for statistical computing and graphics.

2.5.8 *The total global warming potential of multiple cycles of manufacturing wood products*

The benefits of carbon storage (forest residues, wood products, landfills) are estimated in negative global warming potential values. The impacts from GHGs emissions (manufacturing wood products, landfilling, recycling, combustion) are estimated as positive values of the global warming potential. The total global warming potential is calculated by summing both values. This analysis focuses on multiple cycles of manufacturing wood products from Red alder and Douglas fir plantations over 100 years. The global warming potential results are interpreted as impacts on the global warming occurred by wood product use cycles in Washington and Oregon since plantation data is emulated based on the data in Washington and Oregon.

2.6 NET PRESENT VALUE

To comprehend each harvesting age's economic viability, this study calculates discounted cash flow of the first rotation of managing plantations using the net present value (NPV). The equation of NPV is Equation 13.

Equation 13. Estimation of Net Present Value

$$NPV = -E + \sum_{t=1}^{R-1} \frac{I_t}{(1+i)^t} + \frac{A[(1+i)^R - 1]}{i(1+i)^R} + \frac{P_h - C_h}{(1+i)^R}$$

,where E is the initial investment, R is the year of the harvesting age at the first rotation, and i is the discount rate. It is intermediate benefits (return minus cost), A means annual benefits, Ph is harvesting revenue by selling woods, C_h is the cost of harvesting and selling woods. The operating cost is mainly referred to the silvicultural costs survey held in PNW and Diaz et al.(2018).[39], [40] Table 6 indicates each cost. The initial investment is site preparation, and the annual cost is an average annual administrative fixed cost. There is no intermediate revenue. Hence, the intermediate benefits are just the cost that occurred in the middle of the rotation. The intermediate benefit is tree planting, seedling cost, and brush control. The seedling cost is based on the tree seedling prices provided by Washington state nursery companies (DNR). This study uses 5% and 7% for the discount rate based on Industrial reports and previous research for NPV. [40]–[43] The case of Red Alder plantations with thinning uses the pre-commercial thinning cost.

Table 8. Operating cost

Time	Operation	Cost	Unit	Source	Note
Annual	Average annual administrative fixed cost	34	$ / acre / year	Arney (2016)	
Initial	Site preparation	136	$ / acre	Arney (2016)	
2nd year	Tree Planting	154	$ /acre	Arney (2016)	Not including the cost for seedling
2nd year	Seedling cost (Douglas Fir)	379.538	$ / acre	Nursery companies in WA	P+1type, $ 0.873/seedling, 435 tree/acre
2nd year	Seedling cost (Red Alder)	481.25 (high), 196.875 (low)	$ / acre	Nursery companies in WA	1+0 type, $ 0.869/seedling, 550 tree/acre (High density), 225 tree/acre (Low density)"
5th year	Brush control	115	$ / acre	Arney (2016)	Total average in PNW
Thinning year	Pre commercial thinning	170	$ / acre	Arney (2016)	
Harvesting year	Harvesting	177	$ / MBF	Arney (2016)	
Harvesting year	Hauling (transportation)	100	$ / MBF	Diaz (2018)	

The plantations in this study do not contain commercial thinning. Harvesting revenue at harvesting age is the only factor to shift NPV positive. This research estimates the harvesting revenue by Equation 14.

Equation 14. Estimating harvesting revenue

$$P_h = \sum_j \sum_k Log\ price_j \cdot MBF_k \cdot Log\ grade\ distribution_{j,k}$$

Table 9. Log price

Douglas-fir	$ / MBF
SM and better	919.4
2 Saw	833.3
3 Saw	777.3
4 Saw	687.7
Utility/Pulp	413.8
Red alder	**$ / MBF**
2 Saw	741.0
3 Saw	705.0
4 Saw	587.4
Utility/Pulp	263.5

Source: DNR(2023)

Where j represents a log grade class for each tree specie, k is diameter class. $Log\ price_j$ means delivered log price depending on each log grade. This study uses an average delivered log price between April 2022 and March 2023, which are provided in DNR. (Table 9)[44] MBF_k express the merchantable log volume at the diameter class k calculated by CIPSANON and ORGANON. $Log\ grade\ distribution_{j,k}$ is a proportion of log grade of j in the total merchantable log volume of diameter k. Those share of the log grades by diameter class originally comes from the DNR Timber Sales Database provided by the DNR Timber Sales Search

Application.[45] This research took the timber sales information between April 2023 and July 2023, which includes data on average DBH and log volume separated in log grades. The data were averaged and adjusted to the diameter class of forest stands development data by ORGANON and CIPSANON. This study considers the log distribution of diameter less than ten to be the same as that of diameter class: 10 – 12 inches since there is no data for those diameter classes. The results of log distribution are Figure 4 for Red alder and Figure 5 for Douglas-fir. This study standardized GWMP and NPV to compare after finalizing both calculations and sum up both standardized values to detect the most balanced combination of GWMP and NPV in each condition.

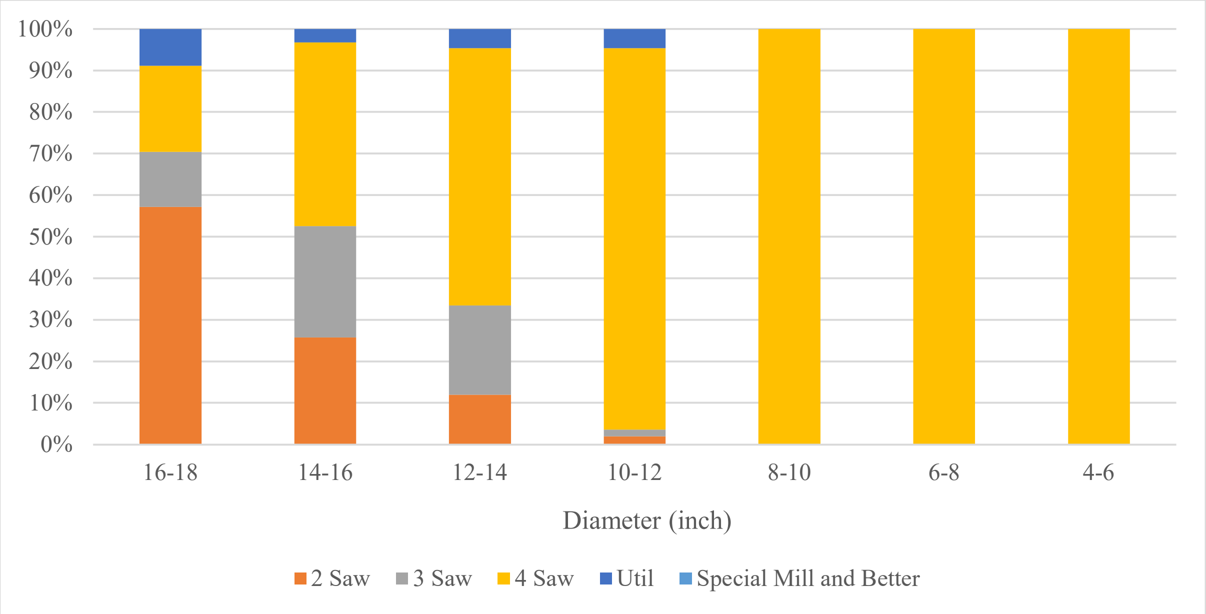


Figure 4. Log grad distribution of Red alder depending on each diameter class

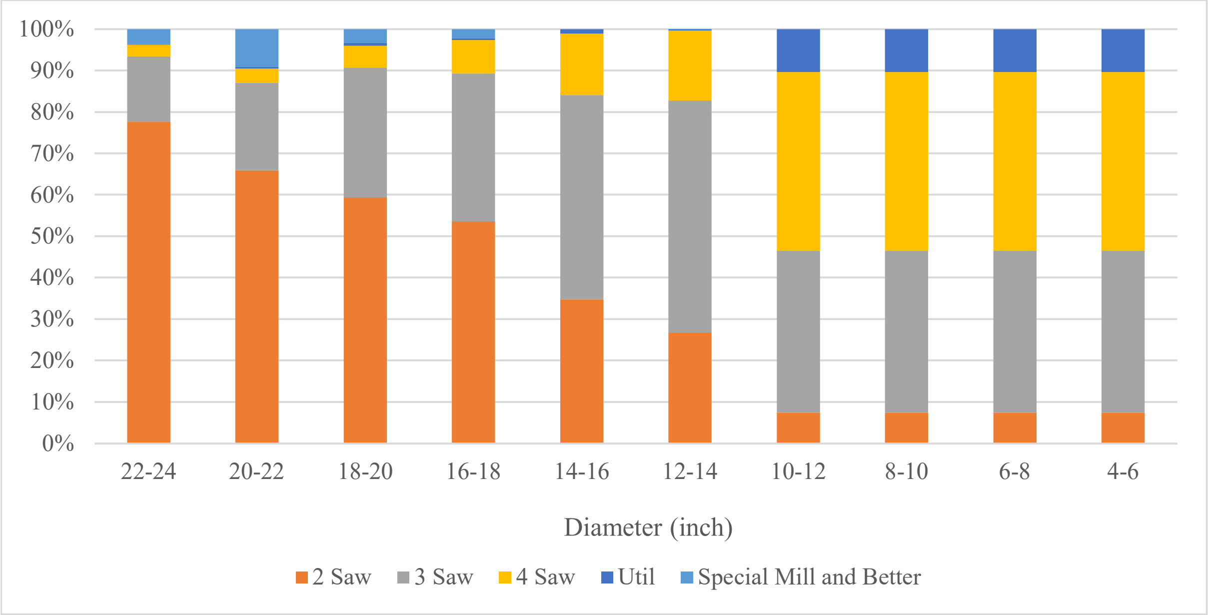


Figure 5. Log grade distribution of Douglas-fir depending on each diameter class

Chapter 3. RESULTS AND DISCUSSION

3.1 CARBON SEQUESTRATION AND GLOBAL WARMING POTENTIAL ESTIMATES FOR RED ALDER VS. DOUGLAS-FIR, BY SITE INDEX CLASSES.

According to the distribution of Site index combinations in the WESTERN WA landscape (Table 10), which was surveyed by others in this research group, 82 % of the area has a site index between 65 and 85 for Red alder, 87% of the area has the Douglas-fir site index between 125 and 145. Considering the combination of site indices, the area with the site index: 65 in Red alder and the site index: 145 in Douglas-fir together exists the most, 14%. The Red alder site index set: 75 and Douglas-fir site index: 145 follow that.[46] This study uses the site indices combination of 65 for Red alder and 145 for Doulas-fir to compare two species.

Table 10. Distributions of site index combination in the Pacific Northwest area

Species		Douglas-fir									Total
	Site Index	85	95	105	115	125	135	145	155	165	
Red alder	35	0.00%	0.01%	0.12%	0.28%	0.16%	0.01%	0.00%	0.00%	0.00%	0.58%
	45	0.01%	0.01%	0.06%	0.34%	0.92%	0.88%	0.13%	0.00%	0.00%	2.37%
	55	0.02%	0.11%	0.24%	0.97%	2.25%	6.39%	3.41%	0.26%	0.00%	13.65%
	65	0.01%	0.10%	0.37%	1.58%	3.96%	12.10%	14.32%	2.67%	0.01%	35.13%
	75	0.00%	0.03%	0.22%	0.82%	2.78%	13.00%	13.78%	3.21%	0.06%	33.90%
	85	0.00%	0.00%	0.08%	0.27%	1.10%	4.97%	5.40%	1.14%	0.05%	13.02%
	95	0.00%	0.00%	0.01%	0.11%	0.49%	0.34%	0.30%	0.10%	0.02%	1.36%
Total		0.03%	0.27%	1.10%	4.37%	11.66%	37.69%	37.35%	7.39%	0.14%	100%

Source: Bormann et al. (2023)

3.1.1 *Long-term (100 years) carbon sequestration and Global Warming Mitigation Potential*

3.1.1.1 Red alder

3.1.1.1.1 Carbon sequestration

The Figure 6, Figure 7, and Figure 8 indicate the carbon sequestration in three cases of Red alder harvested at the age of 30 years in a site index of 65 with the 100-year time horizon. The rotation from the growing plantation until the disposal of wood products is repeated about 3.3 times. The first figure is the plantation with high density and no treatment. The mean of estimated CS for 100 years is 149.9 t CO_2/acre/year. The breakdown of the total aboveground biomass at the harvesting age is bark: 11.1%, branches: 18.0%, foliage: 3.1%, and bole (from Diameter 2-4 inches to Diameter 16 – 18 inches): 67.9%. The second figure represents the high-density plantation where thinning is operated. The CS for 100 years is 113.7 t CO_2 /acre/year. The total aboveground biomass at 30 years drops by 17.9% compared to the former plantation case. It results in a 24.1% decrease in average CS. The thinning expands the share of bole in larger diameter classes compared to the case of no thinning. However, it does not generate an increment in total aboveground biomass since the loss of biomass by thinning outstrips the growth acceleration by thinning. The last one is the low-density plantation with no treatment conditions. The CS for 100 years is 96.8 t CO_2 /acre/year, the lowest amount of these three cases. The low-density plantation induces a higher ratio of bole in greater diameter classes than the case of no treatment in high-density plantation, likewise the case of thinning. Nevertheless, it does not produce superior CS than the others because of the low pace of initial growth of biomass. In every three cases, the landfill markedly enlarges its carbon storage as time progress in the timeframe. The theory in the WARM model that 88% of carbon moved to landfill does not decay triggers the increment.

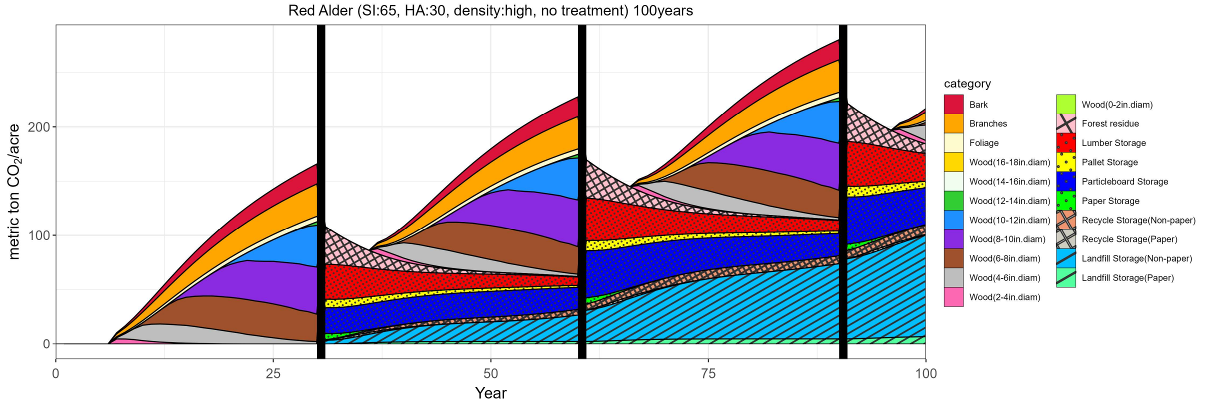


Figure 6. CS100 of Red alder (High density, No treatment)

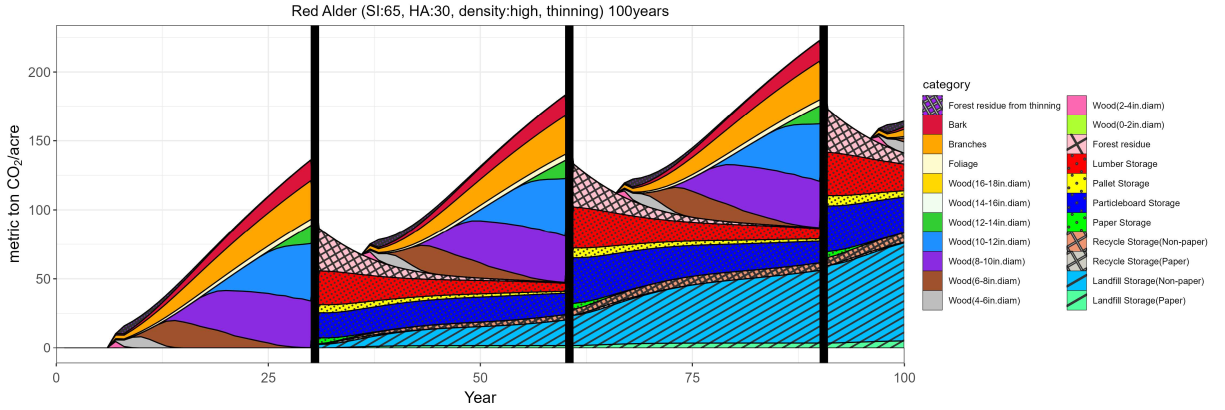


Figure 7. CS100 of Red alder (High density, Thinning)

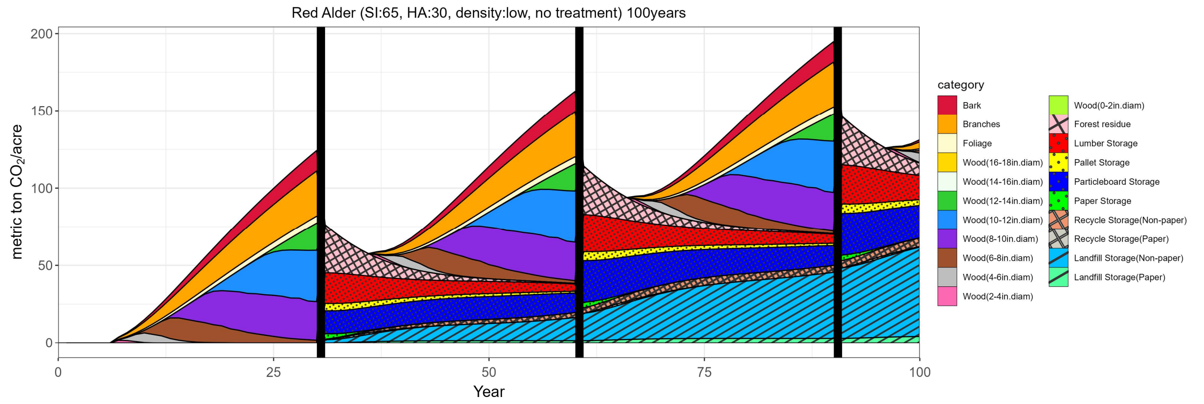


Figure 8. CS100 of Red alder (Low density, No treatment)

Figure 9 illustrates changes in CS100 for three cases of different harvesting ages. The three lines almost parallelly grow as the age increases. The gap of CS for high density with no treatment between 20 and 40 years of harvesting age is 40.9 t CO_2/acre/year. The CS of a high-density plantation with no treatment reaches the apex, 157.9 t CO_2/acre/year, at 34 years of harvesting age, and fluctuates from 34 to 40 years.

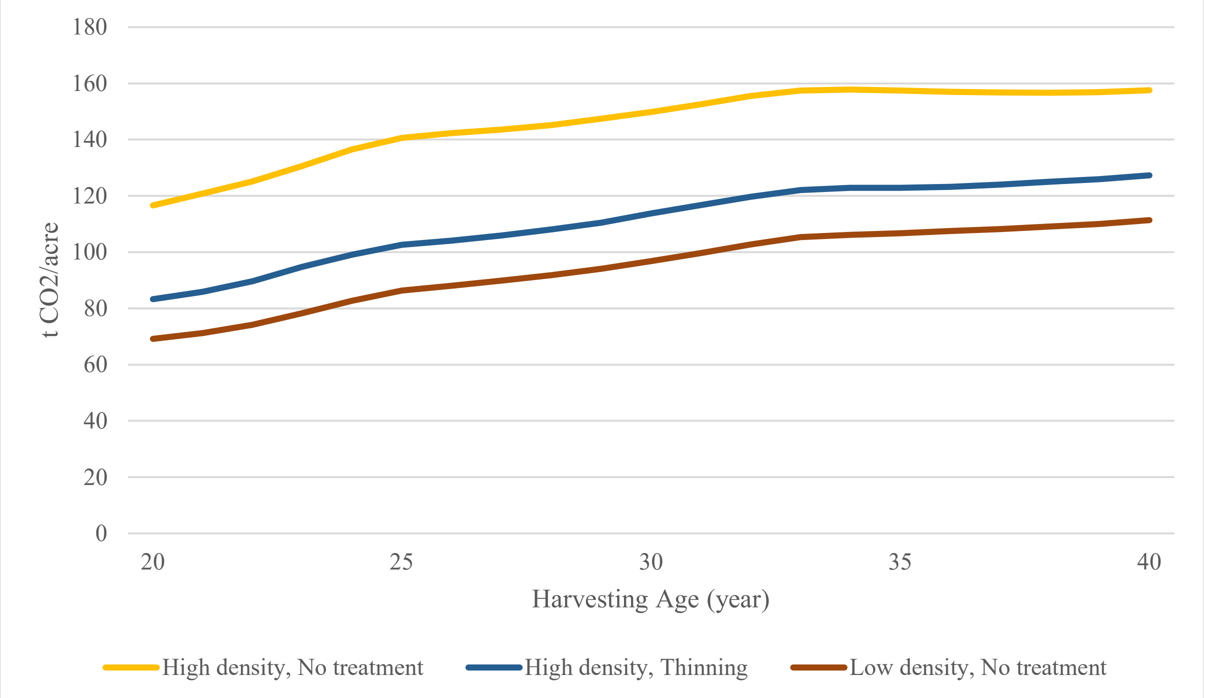


Figure 9.CS100 of Red alder depending on each harvesting age

Rotations with greater harvesting ages tend to gain higher CS100, which is ascribed to fewer harvesting times during 100 years and their higher ratio of merchantable log volume to the total aboveground biomass. The decline of temporal carbon storage after harvesting is significant, especially for the younger harvesting ages. Figure 10 indicates the single rotation of Red alder plantation with 20 years of harvesting age. The area of forest residue is wider, and the ratio of manufactured wood products to the biomass at the harvesting age is less compared to the case of 40 years of harvesting age. (Figure 11) Forest stands in the early stage have smaller bole diameters, resulting in a lower ratio of merchantable log biomass volume to the total aboveground biomass at harvesting ages. It leads to generate more carbon storage of forest residue which relatively decays faster than carbon storage in wood products. Hence, the drop in temporal carbon storage after harvesting becomes significant in cases with lower harvesting ages.

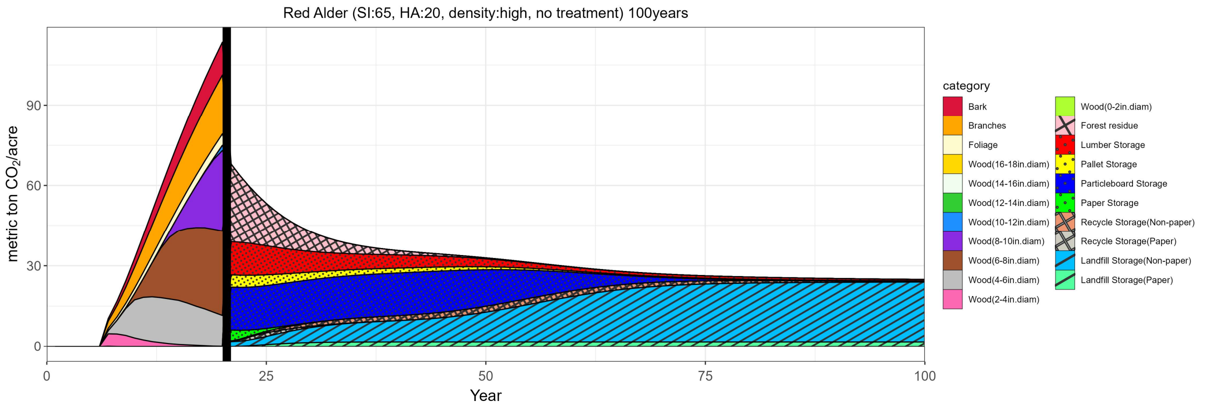


Figure 10. CS100 of Red alder (SI:65, HA:20,High density, No treatment) with single rotation

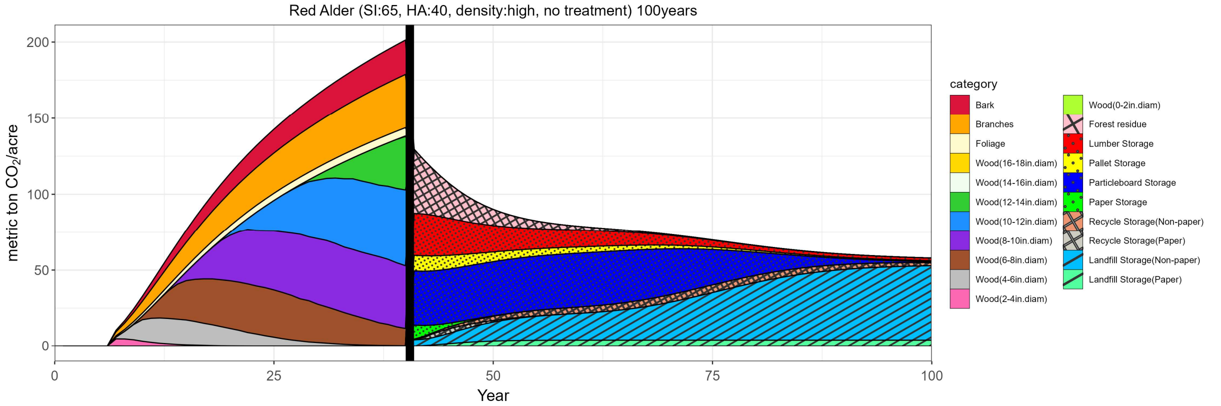


Figure 11. CS100 of Red alder (SI:65, HA:40, High density, No treatment) with single rotation

Figure 12 compares CS100 in Red alder with 20 years of harvesting age and 40 years of harvesting age. Carbon storage associated with wood products and forest residue lifts the temporal carbon storage in successional rotations like a basement. Though lower harvesting age has more opportunities to manufacture wood products, higher harvesting ages create the extensive basement to increase the temporal carbon storage in the next rotation by higher the ratio of merchantable log biomass and the greater total aboveground biomass at the harvesting age, which is enough to outpace the CS100 with early harvesting ages, as shown in Figure 12. The bottom of the temporal carbon storage after the first harvest in the case of harvesting age: 40 years is already more significant than that after the second harvest in the case of harvesting age: 20 years. Hence, prolonging the harvesting age generally leads to an increase in CS100. However, the Red alder site index:65 and 85 case does not follow it.

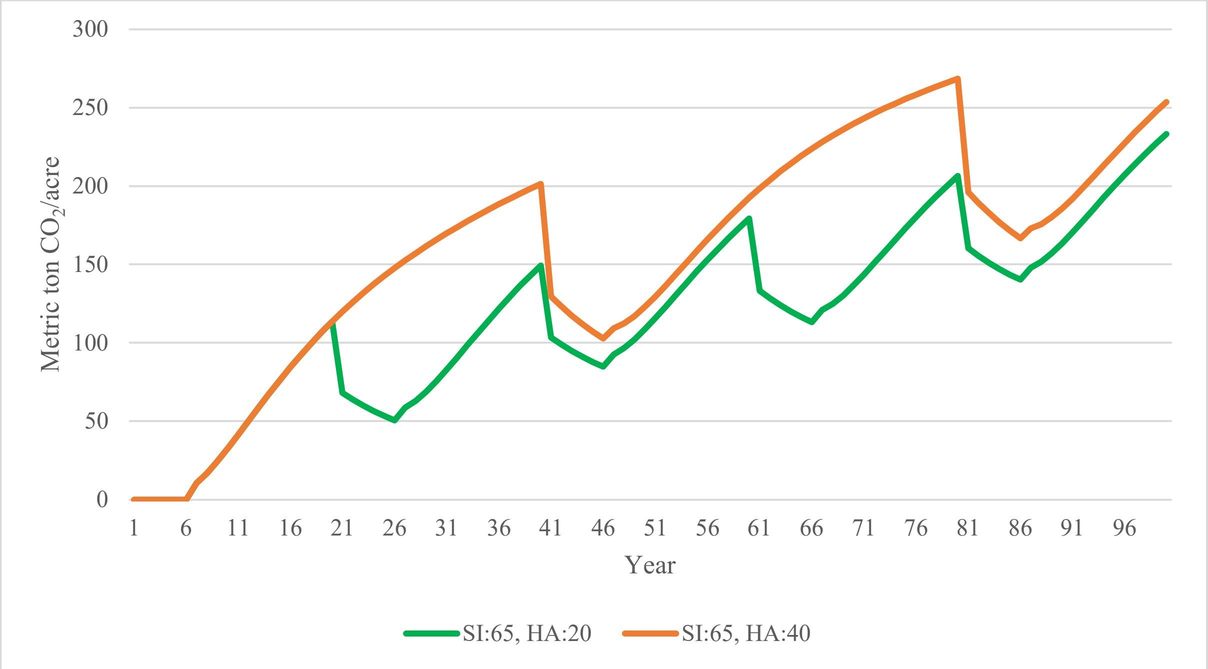


Figure 12. Comparison of CS100 in the case of HA:20 and HA:40 (high density, no

The top of CS100 in among cases of Red alder site index:65 is 157.9 t CO_2/acre/year at 34 years of harvesting age, not at 40 years. The result is ascribed to close merchantable log ratios and a slower rate of biomass growth. The ratio of merchantable log biomass to the total aboveground biomass is stable between 32 and 40 years of harvesting age. There is no big difference between the harvesting age:34 and 40 years. (Figure

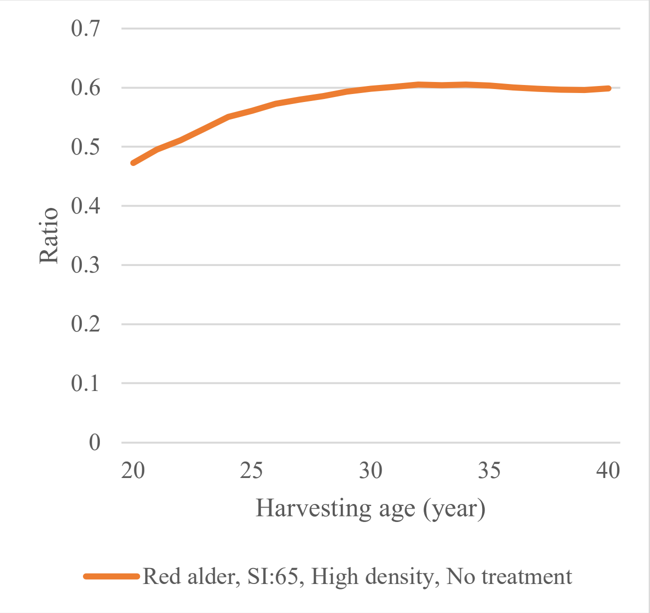


Figure 13. The ratio of merchantable Log to total above ground biomass

13) Regarding the growth rate of the total aboveground biomass, it decreases clearly after 20 years of forest stand ages. It means prolonging the harvesting age after 20 years is less effective than extending the age to less than 20 years. Figure 14 compares the CS100 in the case of harvesting age: 34 years and 40 years. Focusing on the bottom of temporal carbon storage after the first harvest, the difference between two cases is about 10 t CO_2/acre, while the difference of the total aboveground biomass at each harvesting age is about 20 t CO_2/acre. The increment of the total aboveground biomass does not contribute efficiently to raising the temporal carbon storage. In the first and second rotation of the case with 40 years of harvesting age, it grows biomass longer between 35 to 40 years in forest stand age.

On the contrary, the case of 34 years of harvesting age grows plantation longer in the third rotation, from 21 to 32 years in forest stand age. As the growth speed of biomass is faster in the earlier stage, the case of 34 years can benefit from it to increase the total aboveground biomass during the 100 years. As a result, CS100 of the case with 34 years of harvesting age outstrips that of harvesting age: 40 years.

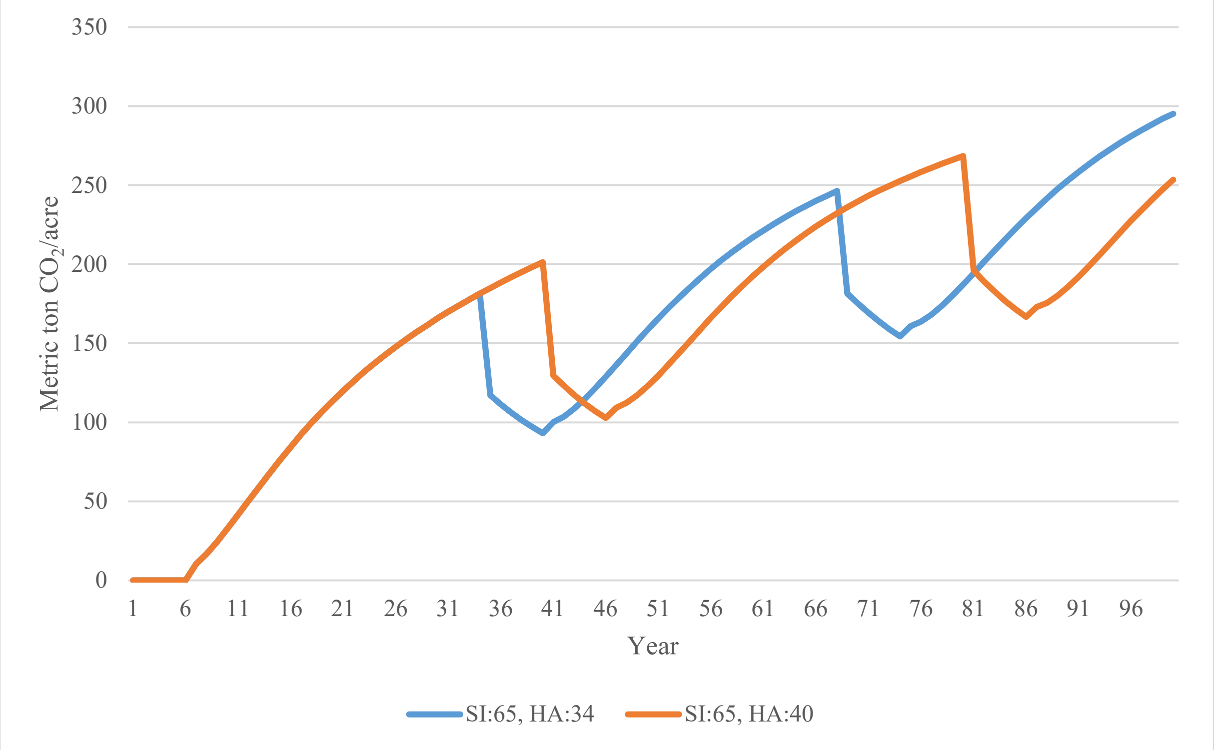


Figure 14. Comparison of CS100 in the case of HA:34, and HA:40 (high density, no

Figure 15 illustrates how CS100 of high-density plantation with no treatment differs according to its site index. As the site index and harvesting age increase, the CS100 also tends to grow. The maximum CS100 in site index:85 is achieved at 33 years of harvesting age, that of site index:65 is at 34 years of harvesting age, and those of the other site indices are at 40 years of harvesting age. The gaps between each site index are relative to the size of site indexes. The difference between CS lines of site index:85 and site index:75 is larger than that of between 35 and 45.

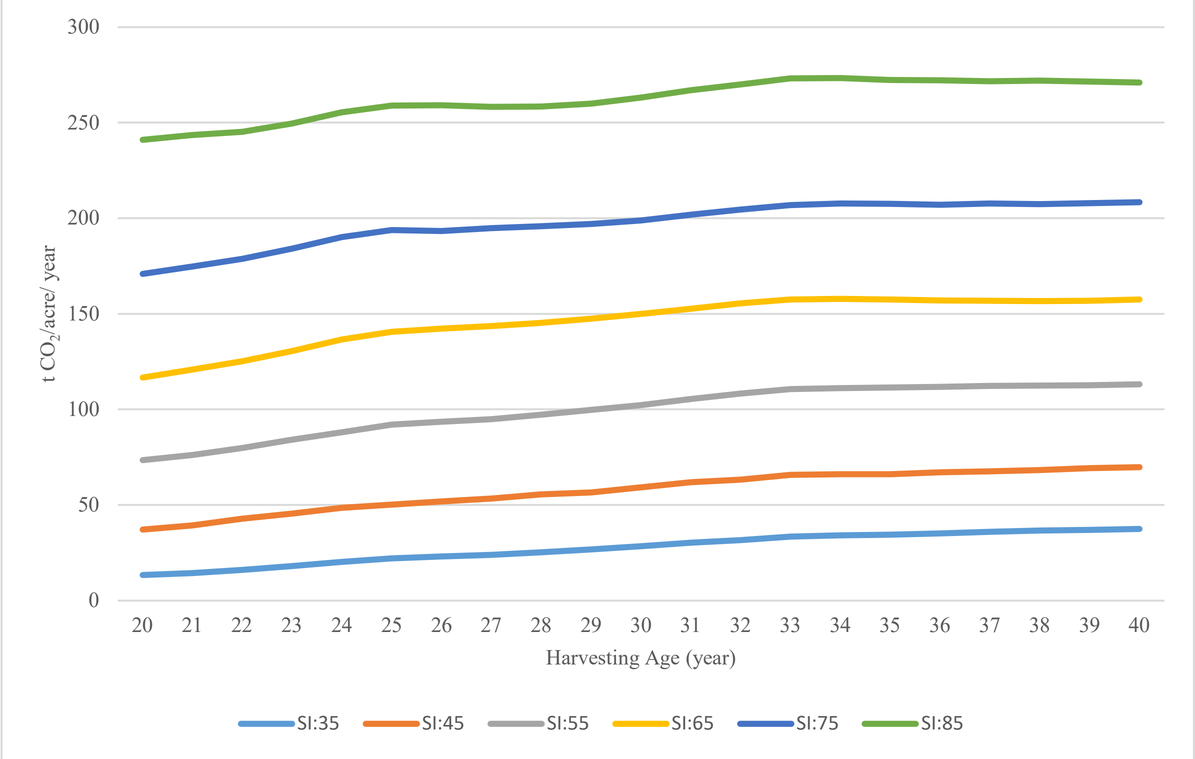


Figure 15. CS100 of Red Alder (High density, No treatment) depending on each site index and harvesting age

3.1.1.1.2 Global Warming Mitigation Potential

The next three figures Figure 16, Figure 17, and Figure 18 show the GWMP in three cases of Red alder harvested at the age of 30 years in a site index of 65 with the100-year time horizon. The positive value along the x-axis means the carbon storage benefit, the opposite negative value means emission impact on global warming. The value in the graph is the radiative forcing. (Unit: W m^{-2} / acre) The first figure is the plantation with high density and no treatment. The estimated GWMP with 100-year time horizon (GWMP100) is 131.6 t CO2eq / acre. The value is the total, which means GWMP subtracted positive value by negative value of emissions. The second figure represents the Red alder high-density plantation with thinning. The GWMP for 100 years is 100.4 t CO2 eq /acre. Thirdly, Figure 18 shows Red alder low-density plantation with no treatment. The

GWMP for 100 years is 88.7 t CO_2 eq /acre, the lowest of the three. The tendency of values that are avoided emissions are similar to those of CS100.

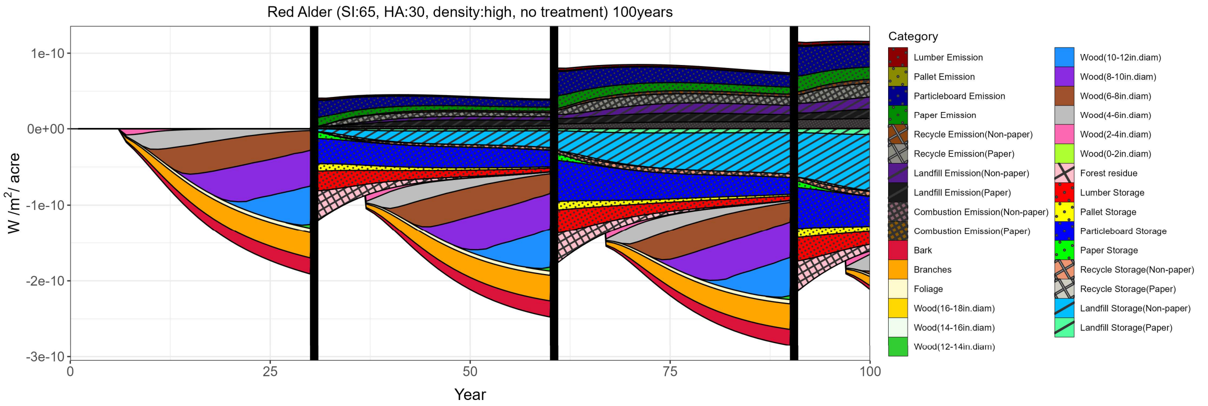


Figure 16. GWMP100 of Red alder (SI:65, HA:30, High density, no treatment)

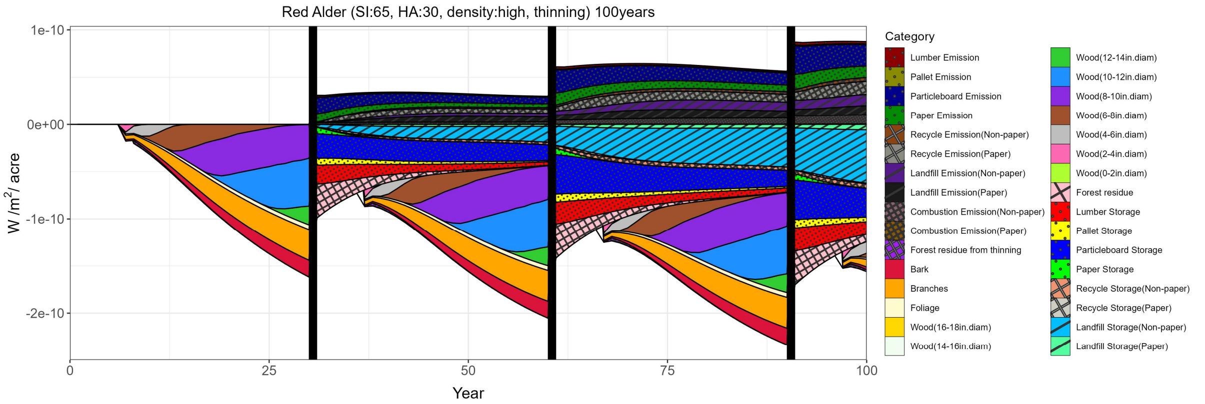


Figure 17.GWMP100 of Red alder (SI:65, HA:30, High density, thinning)

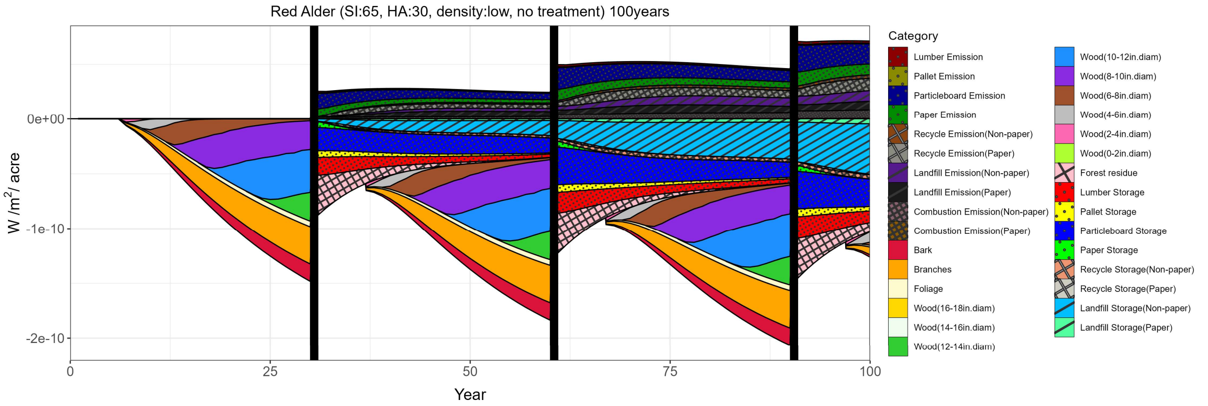


Figure 18. GWMP100 of Red alder (SI:65, HA:30, Low density, no treatment)

Figure 19 shows shifts of GWMP for the three different plantation types in site index:65. The tendency is like those of CS. However, the largest GWMP of the high-density plantation without post-plantation treatments is at 40 years, gaining 147.3 t CO_2 eq/acre, which does not match the harvesting age that maximizes CS100 in the same condition of the plantation.

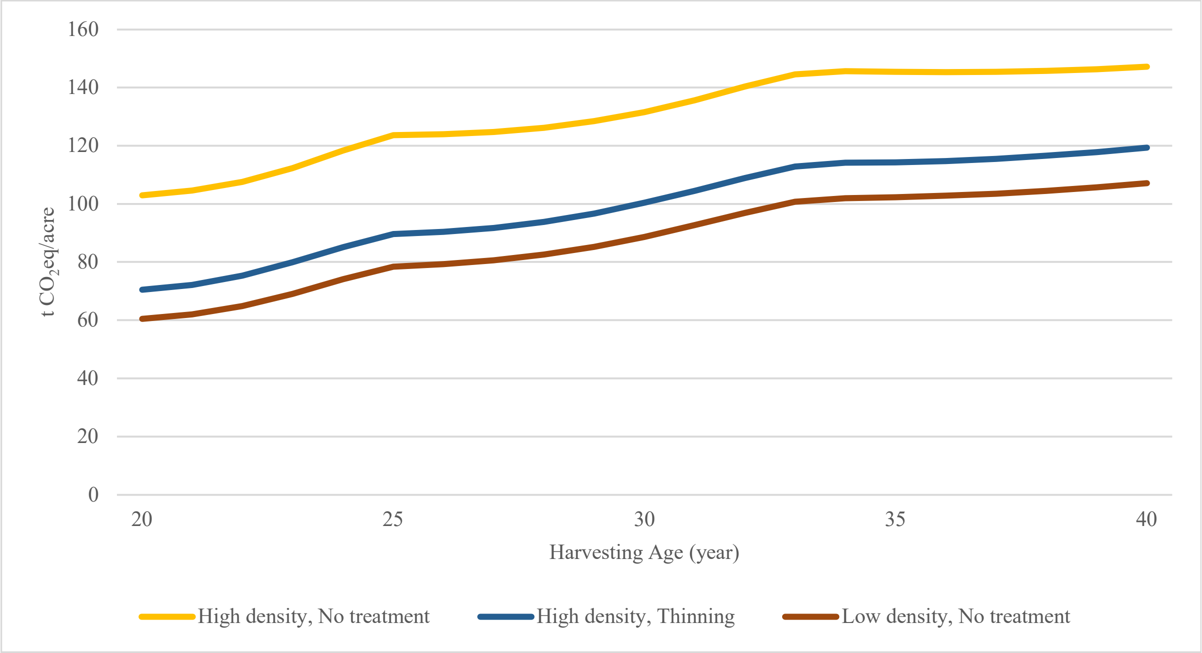


Figure 19. GWP of Red alder (SI:65) depending on each harvesting age

Figure 20 disassembles GWMP100 values of Red alder plantation (SI:65) into carbon storage benefit and emissions impact. As for the carbon storage benefit, it follows the tendency of CS100 in the same condition as plantations. The top of it is at 34 years of harvesting age. Regarding emissions, it increases in harvesting ages larger than 27 years, meaning decreasing the influence to advance global warming. The decrease of carbon storage benefit over the time is accelerated not only by the applied decay function of GHGs, but also by the functional lifetime of wood products, the decay of landfill, and the decay of forest residue. On the contrary, the factor in decreasing emission impact is just the decay function of GHGs. Hence, the emission impact is relatively longer. It results that the timing of releasing emissions influences the total emission impact in GWMP100 values. The earlier harvesting age means manufacturing wood products sooner than greater harvesting age cases, which is equal to releasing emissions earlier. (Figure 21) Therefore, the emissions impact decrease as the harvesting age increases. Though the carbon storage benefit in the case of harvesting age:40 years is less than that of the 34 years case, the increased emissions value offset the difference making the total GWMP100 of the 40 years case more than the 34 years case.

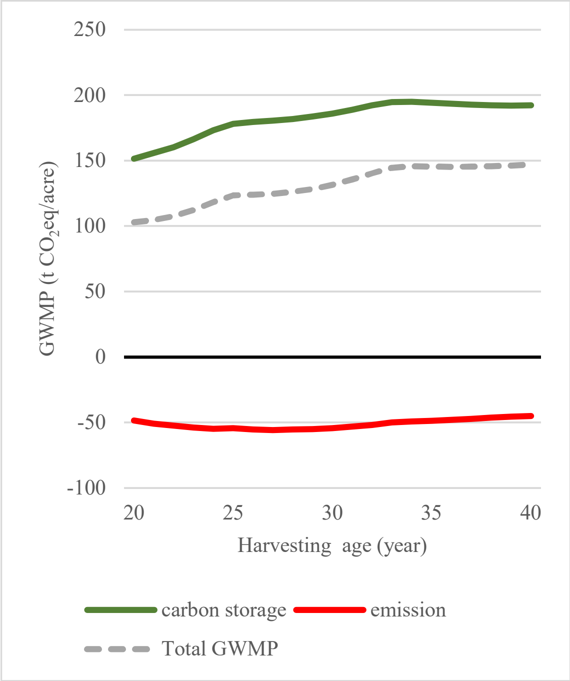


Figure 20. carbon storage benefit and emissions impact in GWMP100 values : RA (SI:65, high density, no treatment)

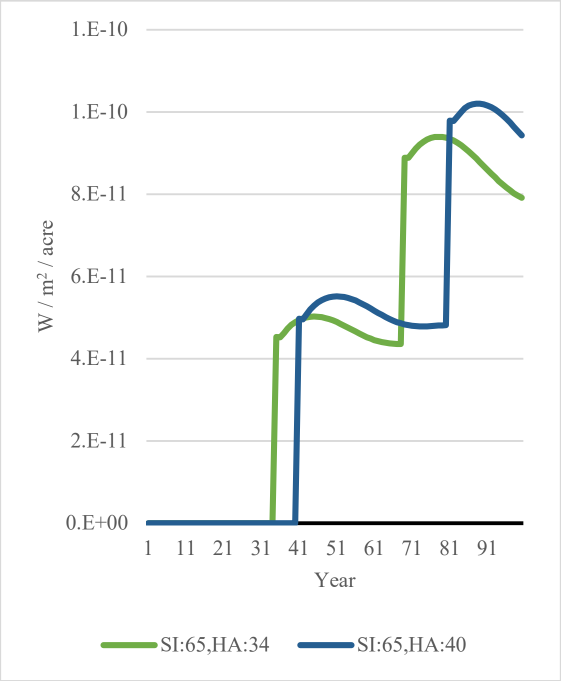


Figure 21. Comparison of emissions in Radiative forcing values :RA (SI65, high density, no treatment)

Figure 22 indicates GWMP change caused by switching harvesting ages on each site index area in the high-density plantation. It also has a similar change trend to the CS100 of Red alder, though the top of GWMP is attained at 40 years of harvesting age in all site indices. This analysis's highest GWMP of Red alder is 245.6 t CO_2 eq /acre in site index:85 at 40 years.

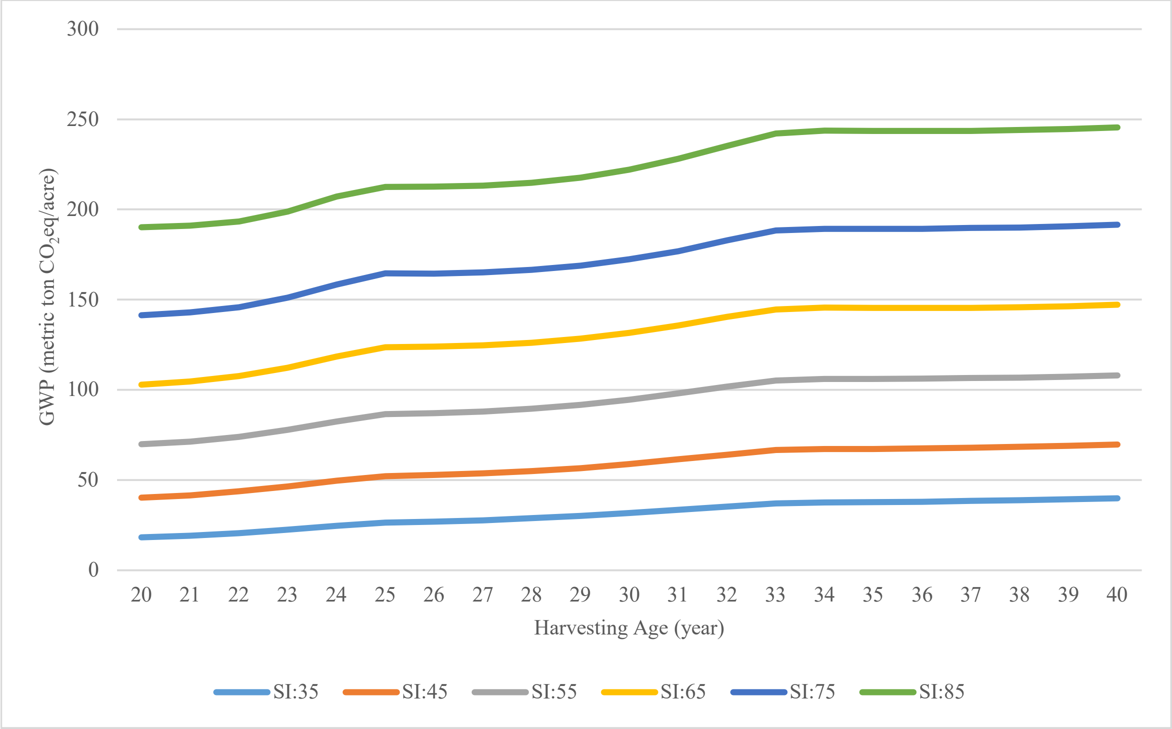


Figure 22. GWMP100 of Red Alder (High density, No treatment) depending on each site index and harvesting age

3.1.1.2 Douglas-fir

3.1.1.2.1 Carbon Sequestration

Figure 23 represents the CS of Douglas-fir in the area of site index:145 with 45 years of harvesting rotation. The average CS for 100 years is 203.1 t CO2/acre/year. Compared to Red alder, the decrease rate of carbon storage in wood products, especially for lumber, is slower owing to its longer functional lifetime. It evades the increment of landfill carbon storage at a high pace. Besides, the proportion of branches accounts for less of the total aboveground biomass at harvesting age.

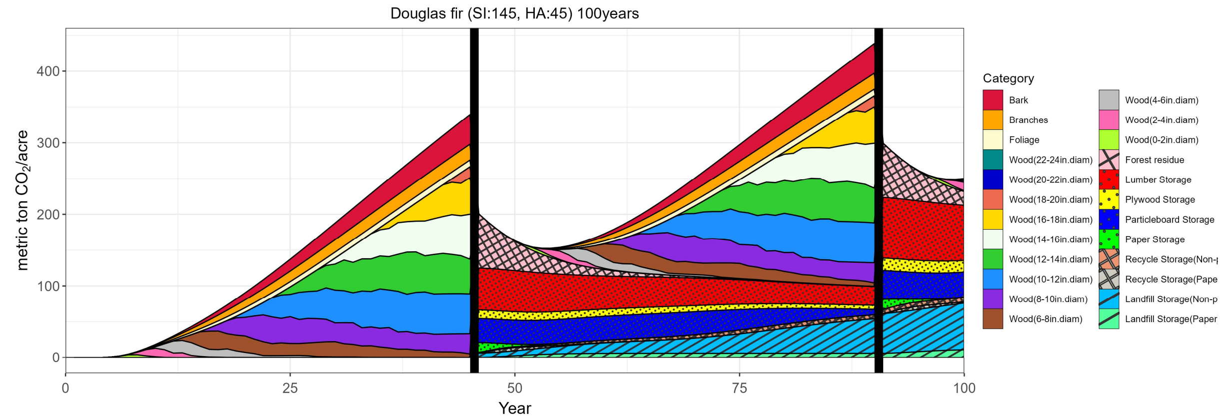


Figure 23. CS100 of Douglas-fir (SI:145, HA:45)

Figure 24 indicates a change in the CS along growing harvesting age in each site index. The CS grows following the ascent of the site index and harvesting age. Hence, The plantation with the highest site index has the highest CS of Douglas-fir in this study, which is 291.9 t CO_2/acre/year when the harvesting age is 55. Though the gaps among site indexes are smaller at early harvesting ages, they grow more prominent as the harvesting age increases.

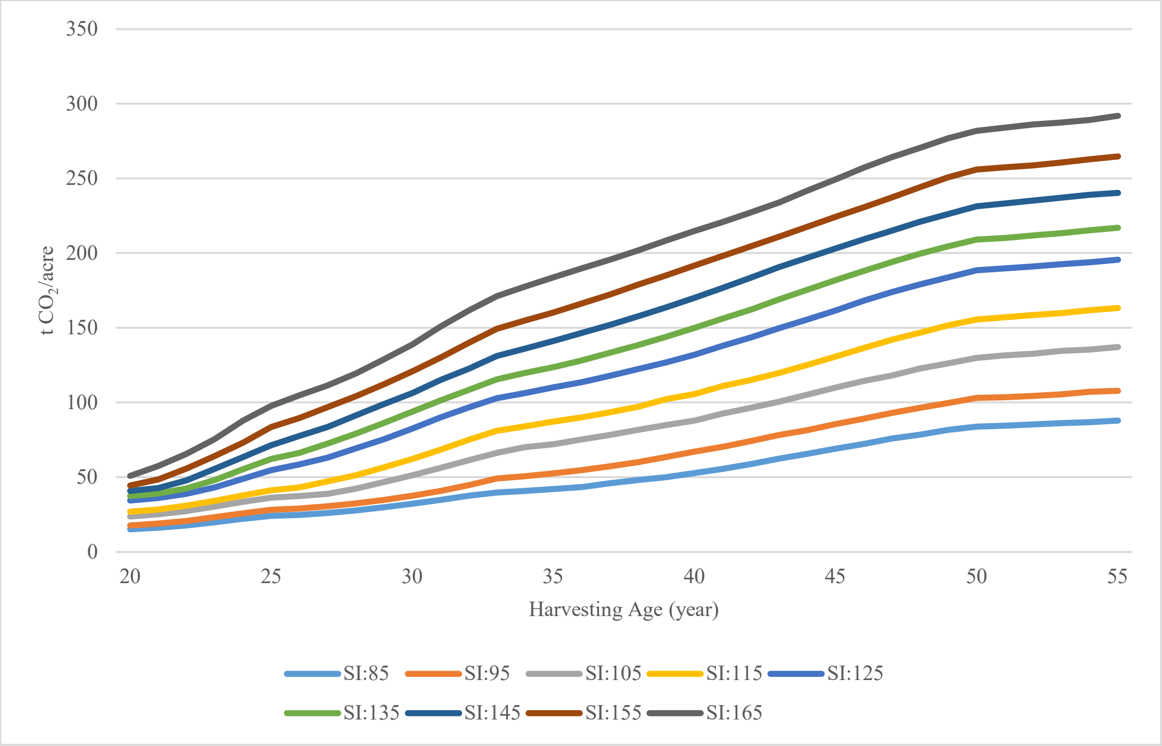


Figure 24.CS100 of Douglas-fir depending on each site index and harvesting age

3.1.1.2.2 Global Warming Mitigation Potential

Figure 25 shows the GWMP of Douglas-fir in site index:145 with harvesting at 45 years. The GWMP100 at the harvesting age is 190.5 t CO_2 eq /acre. The GWMP100 of Douglas-fir differs depending on the combination of site index and harvesting age. The inclination is similar to that of the CS. Their growth is clearly slow after 50 years. They also seem to have different growth rate in a period of 20 – 24 years, a period of 25 – 33, a period of 34 – 49, and a period of 50 – 55. The difference originates in how many times wood products are manufactured for 100 years. The 20 – 24 years period has four times manufacturing, 25 – 33 years has three times, 34 – 49 years has two times, and 50 – 55 years has only one time. Manufacturing transforms the carbon in forest stands into wood products. It stays helping to raise the GWMP in the next cycle as products and landfill. That distinction of growth in GWMP implies that the number of manufacturing times influence significantly.

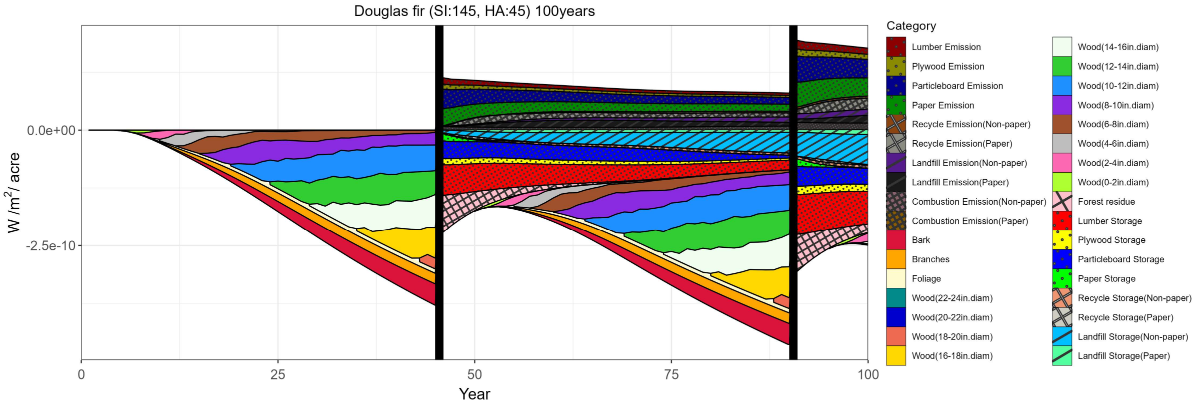


Figure 25. GWMP100 of Douglas-fir (SI:145, HA:45)

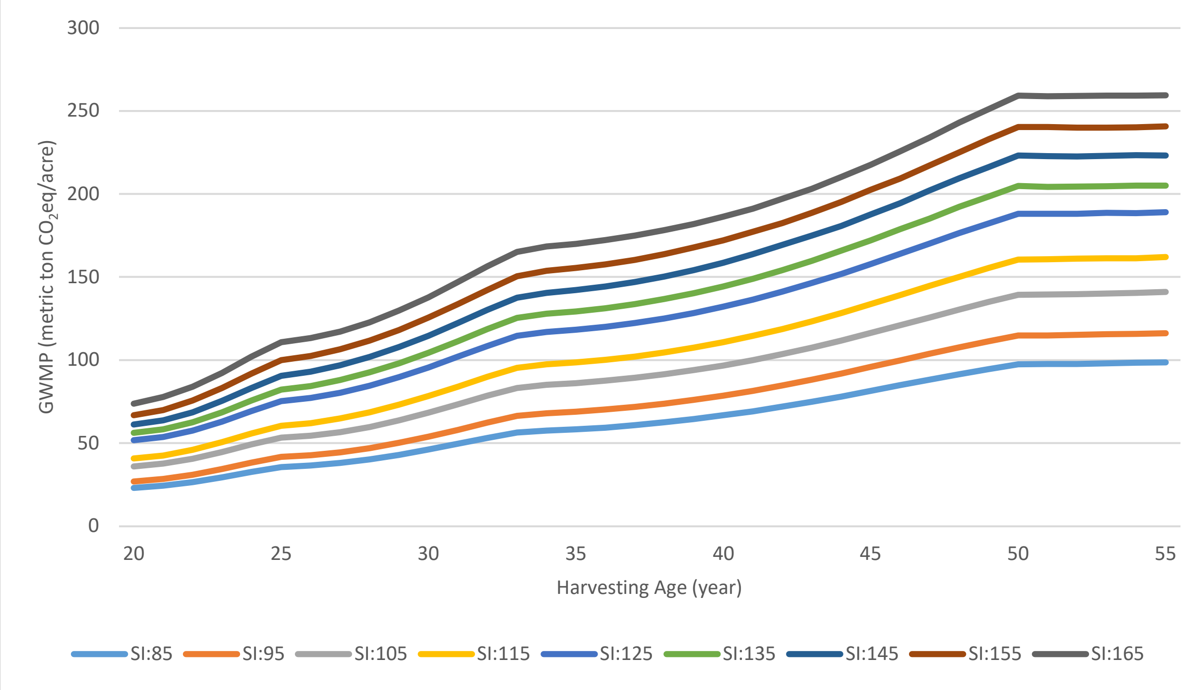


Figure 26. GWMP100 of Douglas-fir, depending on each site index and harvesting age

3.1.2 *Short-term carbon sequestration (25-year time horizon)*

This project estimates CS provided by utilization of forest resources for short-term, 25 years as well. The case of high-density plantation with no treatment shows higher CS than other conditions of Red alder plantation. Hence, this study compares Douglas fir plantation and Red alder high-density plantation with no treatment for short-term CS in two cases, time horizon beginning with planting and time horizon beginning with manufacturing of wood products of Douglas-fir.

Table 11 indicates the result of the comparison of CS with 25 year-time horizons from forestation. The method of estimating CS is the same as the estimation of the 100-year time horizon. Therefore, the estimation includes a process of manufacturing wood products after harvesting ages. The values in the colored cells are calculated by subtracting a mean of CS of Red alder for 25 years by that of Douglas-fir. This study just compares Douglas fir without harvesting to Red alder since a normal harvesting age of Douglas-fir is over 30 years. The orange area is positive value cells meaning the CS of Red alder exceeds that of Douglas-fir. That consequence implies that the Red alder plantation can attain more CS than Douglas-fir if we manage a high-density Red alder plantation without thinning in an area with site index: 65, 75, and 85. Red alder plantation in site index: 45, and 55 can do only if the site index of compared Douglas-fir is less than 125 for Red alder plantation in site index: 55 or less than 95 for Red alder plantation in site index: 45. It depends on the landowner's decision of forest management. This research considers that the site index combination where Red alder can defeat Douglas-fir is that Red alder's CS outpaces the highest Douglas-fir's. Summing up the percentage of area matching with that condition results in 85.7%, according to Table 10. Hence, Red alder has a substantial potential to surpass Douglas-fir, considering CS with the 25-year time horizon starting from forestation.

Table 11. Comparison of carbon sequestration with 25-year time horizon

					Douglas-fir								
				Site index	**85**	**95**	**105**	**115**	**125**	**135**	**145**	**155**	**165**
	Site index	**Density**	**Treatment**	**CS25 (t CO2eq/acre /year)**	27.9	32.6	41.3	46.7	56.8	61.8	67.6	73.6	80.5
Red alder	**35**	High	None	13.7	-12.6	-17.2	-26.0	-31.4	-41.5	-46.5	-52.2	-58.3	-65.2
	35	High	Thinning	9.6	-17.6	-22.3	-31.0	-36.5	-46.6	-51.5	-57.3	-63.4	-70.2
	35	Low	None	8.3	-18.9	-23.6	-32.3	-37.7	-47.8	-52.8	-58.6	-64.6	-71.5
	45	High	None	27.2	1.9	-2.8	-11.5	-17.0	-27.1	-32.0	-37.8	-43.8	-50.7
	45	High	Thinning	20.0	-6.8	-11.5	-20.2	-25.7	-35.8	-40.7	-46.5	-52.5	-59.4
	45	Low	None	18.2	-8.3	-12.9	-21.7	-27.1	-37.2	-42.2	-47.9	-54.0	-60.9
	55	High	None	45.2	20.7	16.1	7.3	1.9	-8.2	-13.2	-18.9	-25.0	-31.9
	55	High	Thinning	32.6	6.3	1.6	-7.1	-12.5	-22.6	-27.6	-33.4	-39.4	-46.3
	55	Low	None	27.5	1.6	-3.1	-11.8	-17.3	-27.4	-32.4	-38.1	-44.2	-51.0
	65	High	None	64.6	40.8	36.1	27.4	21.9	11.8	6.9	1.1	-5.0	-11.8
	65	High	Thinning	46.8	20.4	15.8	7.0	1.6	-8.5	-13.5	-19.2	-25.3	-32.2
	65	Low	None	40.3	14.9	10.2	1.5	-4.0	-14.1	-19.1	-24.8	-30.9	-37.8
	75	High	None	86.5	63.4	58.7	50.0	44.6	34.5	29.5	23.7	17.7	10.8
	75	High	Thinning	65.1	39.5	34.8	26.1	20.6	10.5	5.6	-0.2	-6.2	-13.1
	75	Low	None	59.0	34.4	29.7	21.0	15.5	5.4	0.4	-5.3	-11.4	-18.3
	85	High	None	113.8	91.7	87.0	78.3	72.8	62.7	57.8	52.0	45.9	39.1
	85	High	Thinning	86.0	62.0	57.3	48.6	43.1	33.0	28.1	22.3	16.2	9.4
	85	Low	None	71.4	47.2	42.6	33.8	28.4	18.3	13.3	7.5	1.5	-5.4

Note: there is no harvesting during the 25-year time horizon.

Table 12. Comparison of GWMP with 25-year time horizon

					Douglas-fir								
				Site index	**85**	**95**	**105**	**115**	**125**	**135**	**145**	**155**	**165**
	Site index	**Density**	**Treatment**	**GWMP25 (t CO2eq/acre)**	21.8	25.5	33.0	37.4	46.2	50.1	54.7	59.7	65.3
Red alder	**35**	High	None	15.3	-6.5	-10.2	-17.6	-22.0	-30.9	-34.8	-39.4	-44.3	-50.0
	35	High	Thinning	10.3	-11.6	-15.2	-22.7	-27.1	-35.9	-39.8	-44.4	-49.4	-55.0
	35	Low	None	9.0	-12.8	-16.5	-24.0	-28.4	-37.2	-41.1	-45.7	-50.7	-56.3
	45	High	None	29.8	8.0	4.3	-3.2	-7.6	-16.4	-20.3	-24.9	-29.9	-35.5
	45	High	Thinning	21.1	-0.7	-4.4	-11.9	-16.3	-25.1	-29.0	-33.6	-38.6	-44.2
	45	Low	None	19.6	-2.2	-5.9	-13.4	-17.7	-26.6	-30.5	-35.1	-40.0	-45.7
	55	High	None	48.6	26.8	23.1	15.7	11.3	2.4	-1.5	-6.1	-11.0	-16.7
	55	High	Thinning	34.2	12.4	8.7	1.2	-3.2	-12.0	-15.9	-20.5	-25.5	-31.1
	55	Low	None	29.5	7.6	4.0	-3.5	-7.9	-16.7	-20.6	-25.2	-30.2	-35.8
	65	High	None	68.7	46.8	43.2	35.7	31.3	22.5	18.6	14.0	9.0	3.4
	65	High	Thinning	48.3	26.5	22.8	15.4	11.0	2.1	-1.8	-6.4	-11.3	-17.0
	65	Low	None	42.8	20.9	17.3	9.8	5.4	-3.4	-7.3	-11.9	-16.9	-22.6
	75	High	None	91.3	69.5	65.8	58.3	53.9	45.1	41.2	36.6	31.6	26.0
	75	High	Thinning	67.4	45.6	41.9	34.4	30.0	21.2	17.3	12.7	7.7	2.1
	75	Low	None	62.3	40.4	36.8	29.3	24.9	16.1	12.2	7.6	2.6	-3.1
	85	High	None	119.6	97.7	94.1	86.6	82.2	73.4	69.5	64.9	59.9	54.3
	85	High	Thinning	89.9	68.0	64.4	56.9	52.5	43.7	39.8	35.2	30.2	24.6
	85	Low	None	75.1	53.3	49.6	42.1	37.8	28.9	25.0	20.4	15.5	9.8

Note: there is no harvesting during the 25-year time horizon.

Secondly, this research considers starting the objective time frame from the year of manufacturing wood products instead of the year of establishing the plantation to estimate how much they yield the benefit of CS in 2025 up to 2050. This study focuses on the Douglas-fir's case, of which time horizon begin with the production of wood products at the first cycle of the rotation, assuming Douglas-fir's harvesting age is 45 years. Hence, our example case is that the Douglas-fir's plantation was created in 1980, harvested in 2025, and this research examines the CS from 2025 through 2050 (25-year time horizon). The duration corresponds to between 46 and 70 years in the analysis of the 100-year time horizon. In the case of Red alder, we consider the first plantation was forested in the same year as the Douglas-fir, and calculate each case of different harvesting age from 20 to 40 years. Therefore, the plantation of Red alder started in 1980, harvested and manufactured in a year depending on each case, the target period of CS is the same. As a result, Figure 28 displays the calculated outputs of Red alder by the harvesting ages and site indexes. The highest value is 338.5 t CO2/acre in site index:135 and harvesting age: 35 year. All estimated amounts at harvesting age: 35 demonstrate the maximum in every site index, and the decline trend occurs similarly after that year. The harvesting age of 35 years brings the harvesting timing to the end of the target period to CS and makes the period exclude the manufacturing timing. The moment CS attains the most during one cycle is the harvesting year. In addition, there is a big gap in temporal CS between the harvesting year and the following year. Avoiding the significant reduction and maximizing the storage of forest stands and wood products by including the timeframe just before harvesting age enable harvesting age: 35 achieves the largest volume of CS in all cases of site indexes. Figure 29 represents one of those cases. The mean of CS of Douglas-fir for 25 years is 49.6 t CO2/acre/year in site index:85, 163.2 t CO2/acre/year in site index:135, 184.6 t CO2/acre/year in site index:145, 233.1 t CO2/acre/year in site index:165. The target period contains the process of manufacturing wood products, the beginning of residue decay, and the regeneration. That part is in the relatively low level of CS in the rotations.

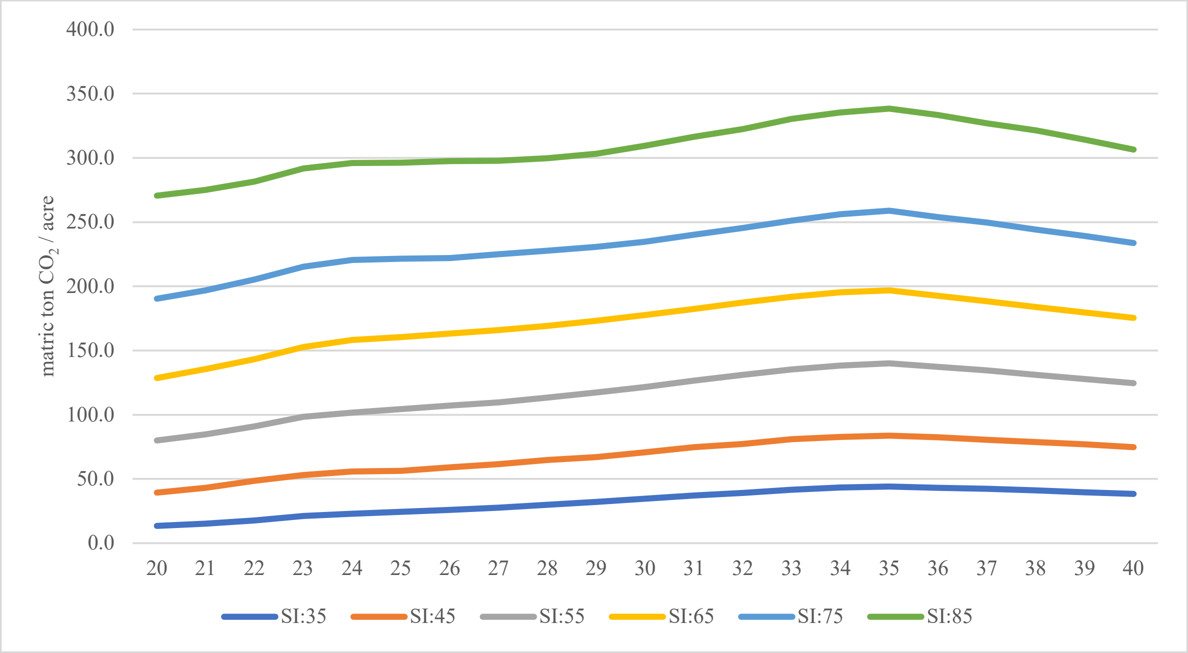
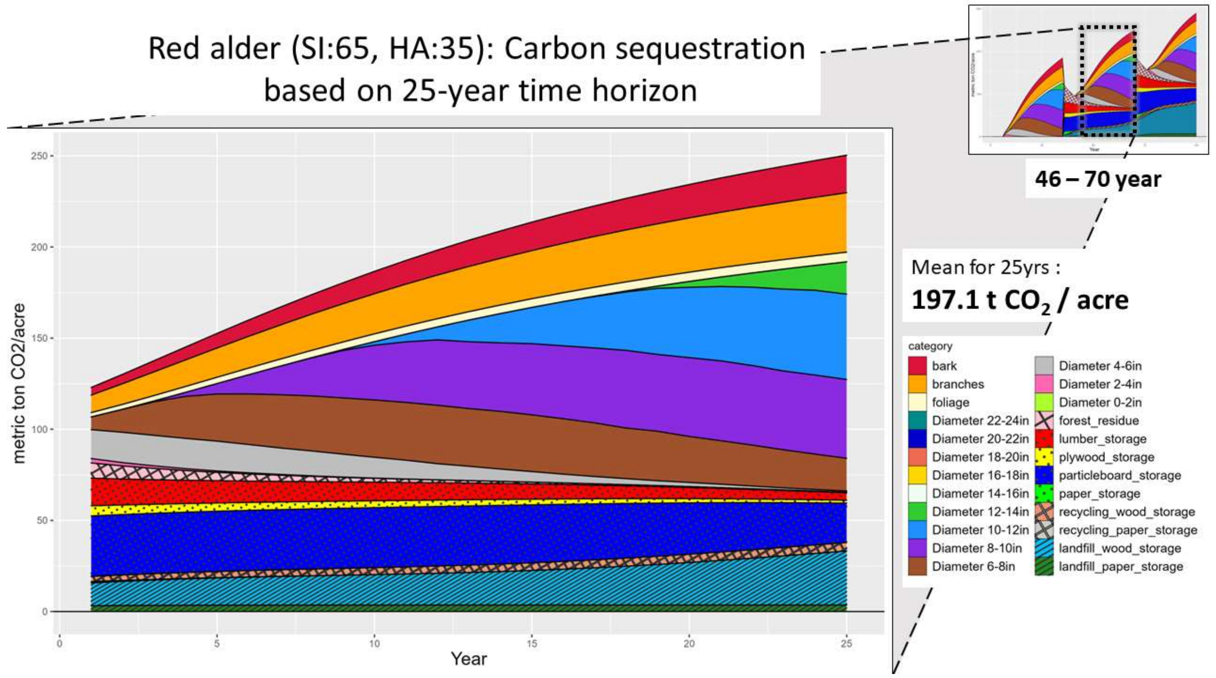


Figure 27. Red alder(high density, no treatment): Carbon sequestration based on 25-year time horizon after manufacturing wood products of Douglas-fir (i.e. 2025 - 2050)



Red alder (SI:65, HA:35): Carbon sequestration based on 25-year time horizon

46 – 70 year

Mean for 25yrs :

197.1 t CO_2 / acre

Figure 28. CS of Red alder (SI:65, HA:35, high density, no treatment) with 25-year time horizon starting after manufacturing wood products of Douglas-fir (i.e. 2025 - 2050)

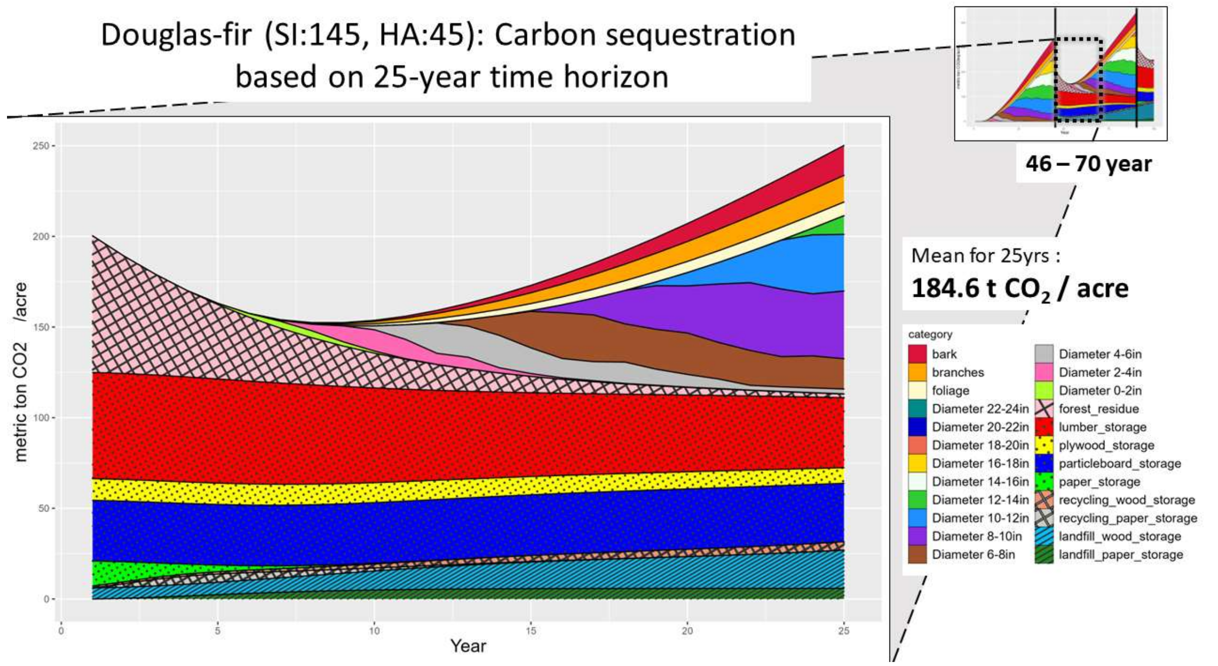


Figure 29. CS of Douglas-fir (SI:145, HA:45) with 25-year time horizon starting after manufacturing wood products (i.e. 2025 - 2050)

Figure 30 compares two species in the area with the mix of site index:145 for Douglas-fir and site index: 65, which has the largest share in WESTERN WA. While Red alder changes along with harvesting ages, Douglas-fir is stable as we just focus on harvesting age 45 years for it. It exhibits that Red alder outstrips Douglas-fir during 32 and 37 years. The peak value of Red alder is 197.1 t CO$_2$/acre at 35 years, which is larger by 12.4 t CO$_2$/acre than 184.6 t CO$_2$/acre for Doulas-fir.

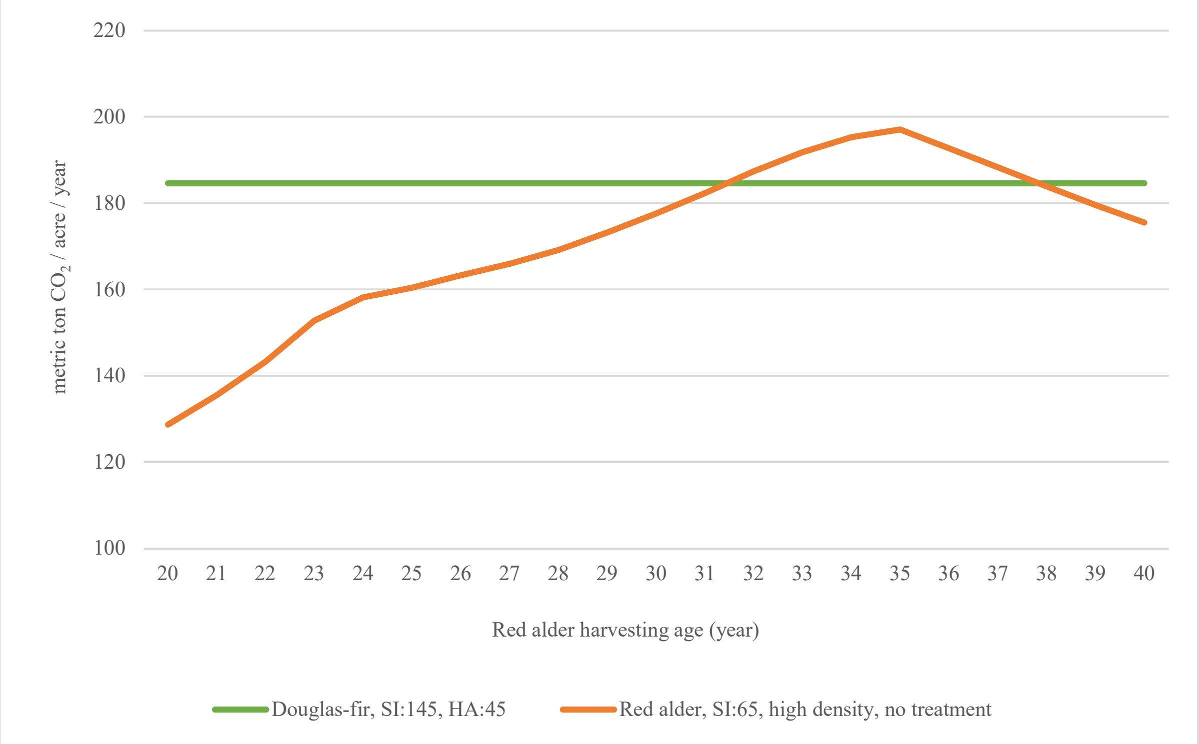


Figure 30. Comparison of CS25 (i.e. 2025 - 2050 starting in 1980)

We also calculate the difference of the CS between Red alder (harvesting age:35) and Douglas-fir (harvesting age:45) in every site index combination. Table 13 displays the results with colors to show the higher one clearly. The total area where Red alder is superior than Douglas-fir in CS consequently accounts for 81.1% of share in WESTERN WA assuming that all Red alder's values in site index:95 excel, while Douglas-fir can make up 18.9%. Hence, Red alder obviously has a greater possibility to store more carbon than Douglas-fir when this study focuses on the timeframe after manufacturing wood products of Douglas-fir.

Table 13. Comparison of Carbon sequestration based on 25-year time horizon starting after harvesting age of Douglas-fir (45 years)

					Douglas-fir									
					Site index	85	95	105	115	125	135	145	155	165
					Harvesting age	45	45	45	45	45	45	45	45	45
Red alder	Site index	Density	Treatment	Harvesting age	Carbon sequestration (t CO_2 /acre)	49.6	65.0	89.7	109.9	142.1	163.2	184.6	206.1	233.1
	35	High	No treatment	35	44.1	-5.5	-20.9	-45.6	-65.7	-98.0	-119.0	-140.5	-161.9	-189.0
	45	High	No treatment	35	83.9	34.3	18.8	-5.9	-26.0	-58.3	-79.3	-100.8	-122.2	-149.2
	55	High	No treatment	35	140.2	90.5	75.1	50.4	30.3	-2.0	-23.0	-44.5	-65.9	-92.9
	65	High	No treatment	35	197.1	147.5	132.0	107.3	87.2	54.9	33.9	12.4	-9.0	-36.0
	75	High	No treatment	35	259.1	209.5	194.1	169.4	149.2	117.0	96.0	74.5	53.0	26.0
	85	High	No treatment	35	338.5	288.9	273.5	248.8	228.6	196.4	175.4	153.9	132.4	105.4

3.1.3 *Comparison of Red alder and Douglas-fir in CS and GWMP*

Figure 31 and Figure 32 show the change of CS100 and GWMP100 of both species along the harvesting age. CS100 of Red alder outstrips that of Douglas-fir between 20 years and 36 years. The GWMP also has the same tendency. Red alder is superior from 20 years to 36 years than Douglas-fir in terms of the GWMP. Change in the CS and the GWMP of Red alder is moderate compared to the Douglas-fir. That factors in the growth of the total aboveground biomass and the ratio of merchantable log biomass to the total aboveground biomass. The growth speed of the total aboveground biomass in Douglas-fir is significantly faster than that of Red alder, as Figure 33 indicates. The total merchantable log volume (BFV) derived from total aboveground biomass are a decisive factor for both CS and the GWMP since the forest product volume manufactured after harvesting depends on it. Total BFV in Red alder is greater than Douglas-fir between 20 and 33 years in harvesting ages, which is a longer period than the total aboveground biomass. (Figure 34) Considering the ratio of the merchantable log to the total aboveground biomass, Red alder is significantly higher than Douglas-fir. Red alder's ratio ranges from 0.45 to 0.6, while Douglas-fir drastically grows from 0 to 0.6 as harvesting age increases. (Figure 35) Despite Douglas-fir having an advantage in total aboveground biomass of older plantations than 27 years of tree age, Red alder surpasses it in CS100 until 37 years and in GWMP100 until 36 years of harvesting age thanks to this higher ratio.

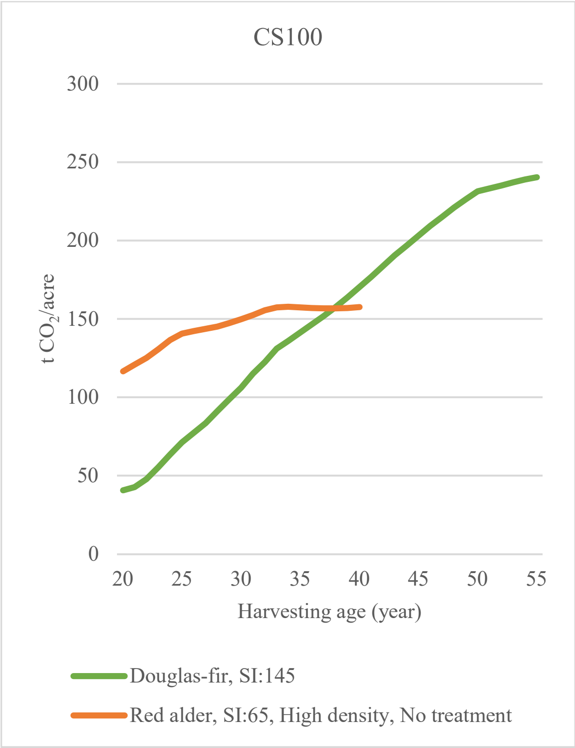


Figure 31. Comparison of the CS100 in each harvesting age

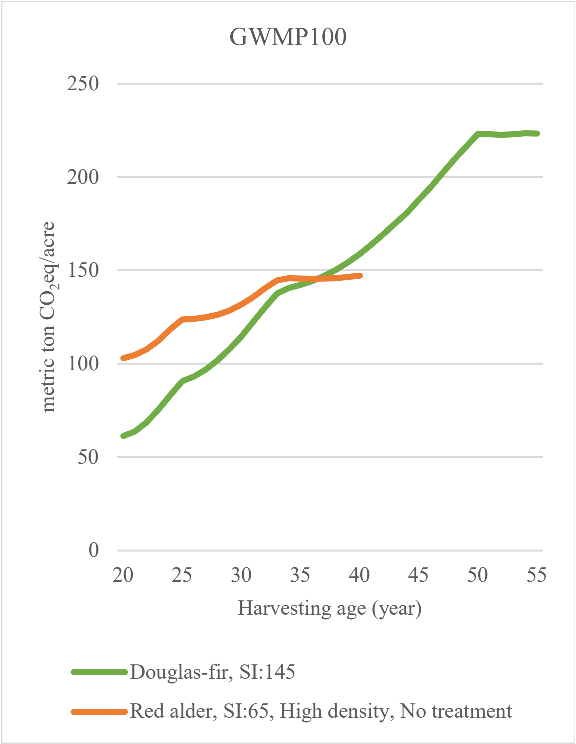


Figure 32. Comparison of the GWMP100 in each harvesting age

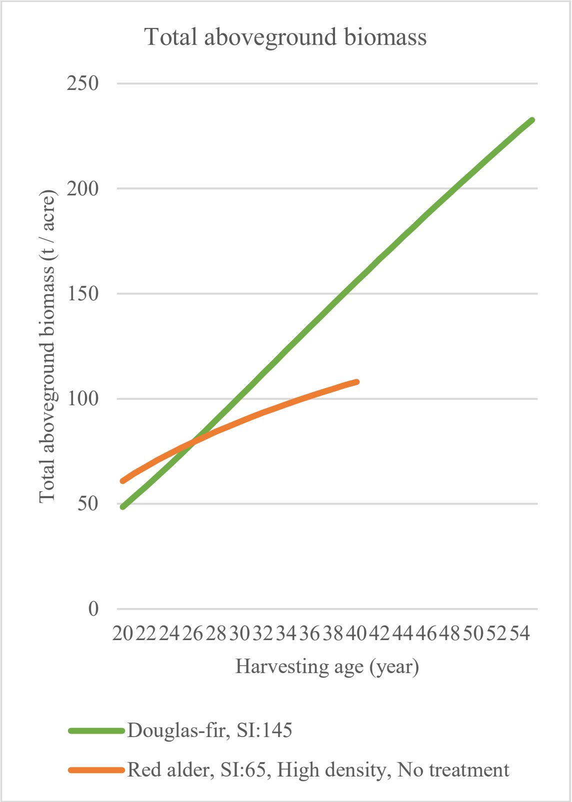


Figure 33. Total aboveground biomass in each harvesting age

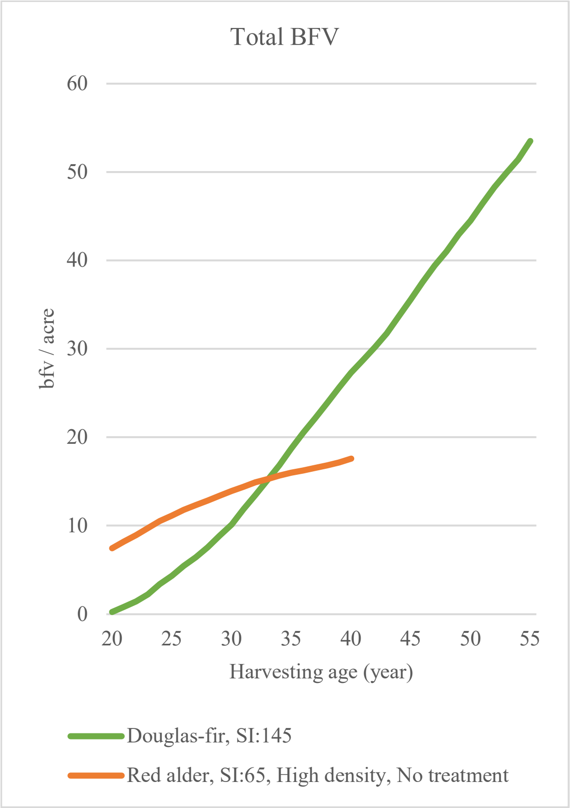


Figure 34. Total BFV in each harvesting age

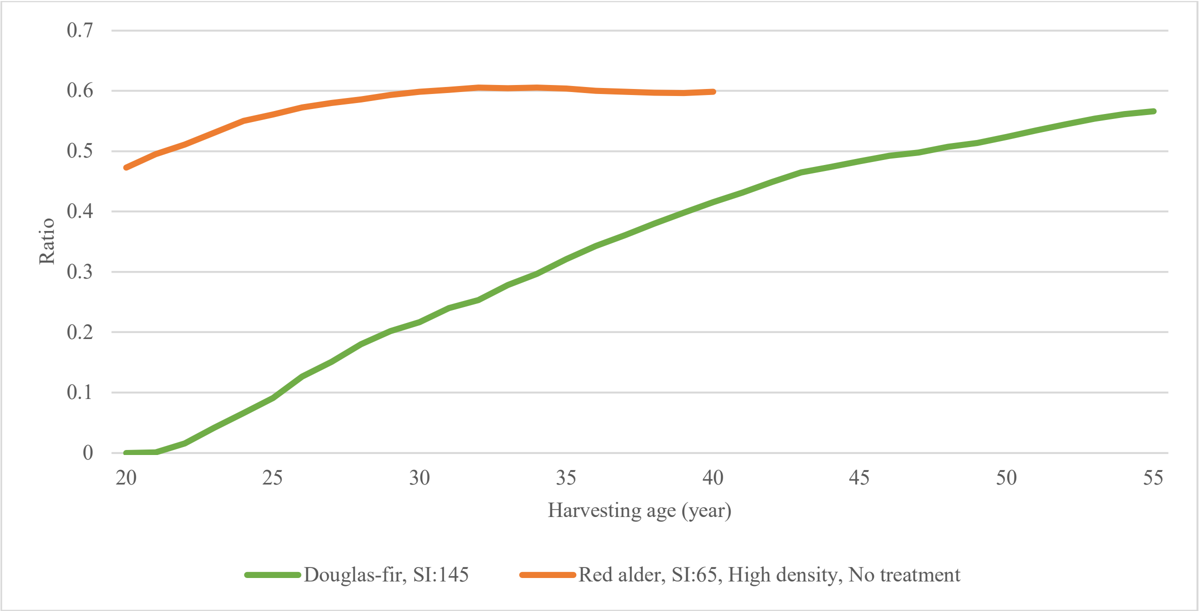


Figure 35. The ratio of merchantable log biomass to total aboveground biomass

Table 14 and Table 15 display the difference in CS100 and GWMP100 between Red alder and Douglas-fir when harvested under the industry-preferred harvesting ages (i.e., Red alder 30 years and Douglas-fir 45 years), respectively. The bold values mean that Red alder excels 20% more than Dougals-fir. Table 14 compares carbon sequestration with 25-year time horizon. Table 15 compares GWMP100 for both species depending on each site index combination. The orange area means Red alder is better than that of Douglas-fir. The green area expresses the opposite result. The percentage coming from Table 10 is the possibility of the existence of each site index combination in WESTERN WA. The row of site index 95 in Red alder is vacant since this study does not have plantation data. However, site index combinations with it exist. This study contains it as a reference. Summing up, the percentages in orange cells shows 30.4 % in total, while the sum of green cells shows 68.3 %. 1.36% has remained as this research does not have comparison data for site index:95 in Red alder. However, this study can predict that the Red alder plantations in site index: 95 presumably outstrip Douglas-fir since all the Red alder plantations in site index:85 outperformed Douglas-fir. Hence, if this analysis assumes Red alder is superior at the site index: 95, this study can add 1.36 % to 31.7 %. As a result, the possibility that Red alder has more global warming mitigation potential than Douglas-fir in WESTERN WA with the 100-year time horizon is 31.7 % under the typical harvesting age conditions.

Table 14. Comparison of the CS100 in the typical harvesting ages

			Douglas-fir								
		Site index	85	95	105	115	125	135	145	155	165
Red alder	**Site index**	**CS100** (t CO_2/acre/year)	69.1	85.4	110.0	130.6	161.5	181.8	203.1	224.1	249.4
	35	28.5	-40.6	-56.9	-81.5	-102.2	-133.1	-153.3	-174.6	-195.7	-220.9
	45	59.1	-10.0	-26.3	-50.9	-71.5	-102.4	-122.6	-144.0	-165.0	-190.2
	55	102.2	**33.1**	**16.8**	-7.8	-28.4	-59.3	-79.6	-100.9	-121.9	-147.2
	65	149.9	**80.8**	**64.5**	**39.9**	19.2	-11.7	-31.9	-53.2	-74.3	-99.5
	75	198.8	**129.7**	**113.4**	**88.8**	**68.2**	**37.3**	17.1	-4.3	-25.3	-50.6
	85	263.2	**194.1**	**177.8**	**153.2**	**132.5**	**101.6**	**81.4**	**60.0**	39.0	13.8

Note: The harvesting age of RA is 30 years, and that of DF is 45 years. Conditions of the plantations is no thinning and no post plantation treatment.

Table 15. Comparison of the GWMP100 in the typical harvesting ages

			Douglas-fir								
		Site index	85	95	105	115	125	135	145	155	165
Red alder	**Site index**	**GWMP100** (t CO2eq/acre)	81.4	95.8	116.2	133.6	157.7	172.0	187.7	202.5	217.6
	35	31.8	-49.7	-64.0	-84.5	-101.8	-126.0	-140.2	-156.0	-170.7	-185.8
	45	58.8	-22.7	-37.0	-57.5	-74.8	-99.0	-113.2	-129.0	-143.7	-158.8
	55	94.5	13.1	-1.3	-21.7	-39.1	-63.2	-77.5	-93.2	-108.0	-123.1
	65	131.6	**50.2**	**35.8**	15.4	-2.0	-26.1	-40.4	-56.1	-70.9	-86.0
	75	172.5	**91.0**	**76.7**	**56.2**	38.9	14.8	0.5	-15.3	-30.0	-45.1
	85	222.0	**140.6**	**126.2**	**105.8**	**88.4**	**64.3**	**50.0**	34.3	19.5	4.4

Note: The harvesting age of RA is 30 years, and that of DF is 45 years. Conditions of the plantations is no thinning and no post plantation treatment.

Table 16. Comparison of the each highest GWMP100 at each site index combination

Species		Douglas-fir									
	Site Index	85	95	105	115	125	135	145	155	165	Total
Red alder	35	0.00%	0.01%	0.12%	0.28%	0.16%	0.01%	0.00%	0.00%	0.00%	0.58%
	45	0.01%	0.01%	0.06%	0.34%	0.92%	0.88%	0.13%	0.00%	0.00%	2.37%
	55	0.02%	0.11%	0.24%	0.97%	2.25%	6.39%	3.41%	0.26%	0.00%	13.65%
	65	0.01%	0.10%	0.37%	1.58%	3.96%	12.10%	14.32%	2.67%	0.01%	35.13%
	75	0.00%	0.03%	0.22%	0.82%	2.78%	13.00%	13.78%	3.21%	0.06%	33.90%
	85	0.00%	0.00%	0.08%	0.27%	1.10%	4.97%	5.40%	1.14%	0.05%	13.02%
	95	0.00%	0.00%	0.01%	0.11%	0.49%	0.34%	0.30%	0.10%	0.02%	1.36%
Total		0.03%	0.27%	1.10%	4.37%	11.66%	37.69%	37.35%	7.39%	0.14%	100%

Figure 36 and Figure 37 illustrate the breakdown of GWMP100 for both species. The category ‘Wood products’ in the figures is the GWMP related to wood products, including storage and emissions of wood products, landfill, recycling, and combustion. Though the harvesting age is different, Branches and the wood products in Red alder play a more prominent role than those of Douglas-fir in the GWMP100. On the contrary, the share of Red alder bole is less. Considering other harvesting age conditions, higher harvesting ages lead to less share of wood products and more share of bole in GWMP100 of both species. (Figure 38 and Figure 39) The forest residue in

Douglas-fir shows a significant decrease as harvesting ages increase since the ratio of merchantable log volume to total aboveground biomass grows along the ages. The share of branches is almost stable in any harvesting age rotation cases.

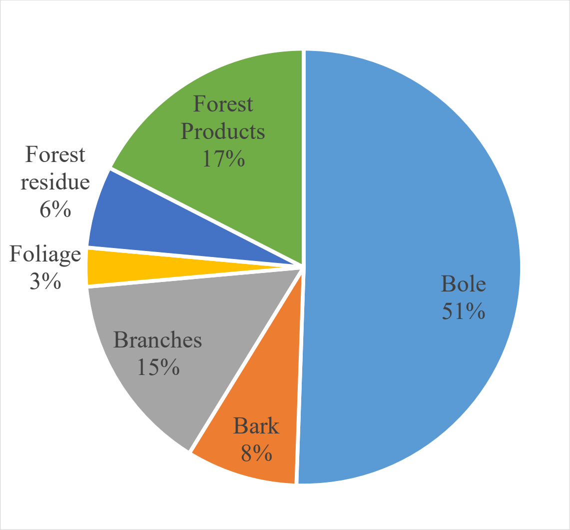


Figure 36. GWMP100 breakdown in the case of Red alder (SI: 65, HA: 30, high-density plantation, no treatment)

Note: The category ,Forest products , contains storage of each Redd alder wood product, landfill and emissions of manufacturing products, landfill, recycling, and combustion.

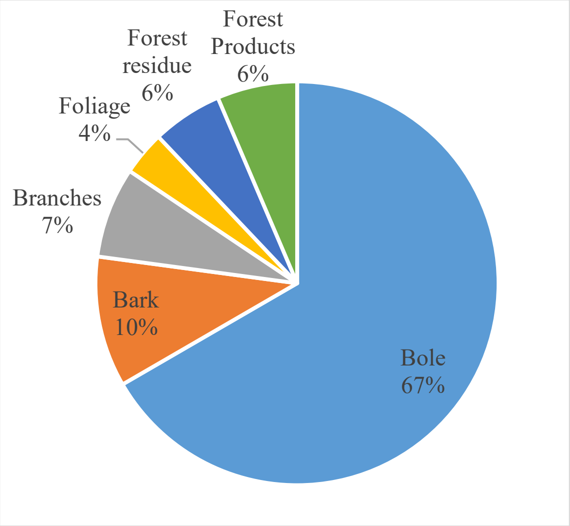


Figure 37. GWMP100 breakdown in the case of Douglas-fir (SI: 145, HA: 45)

Note: The category ,Forest products , contains storage of each Douglas-fir wood product, landfill and emissions of manufacturing products, landfill, recycling, and combustion.

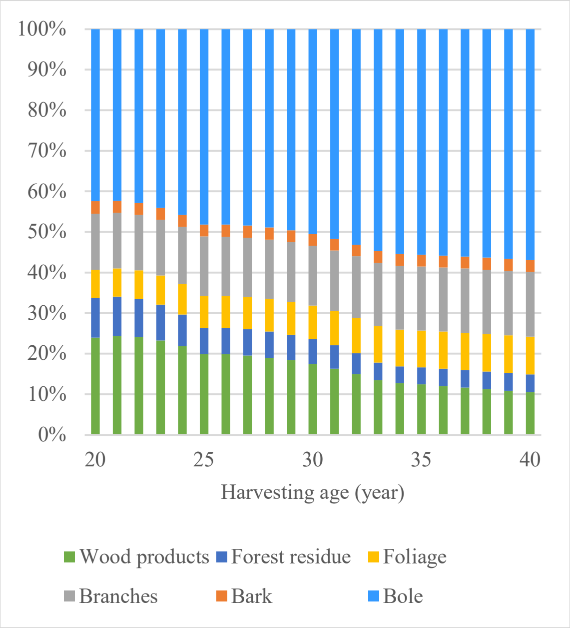


Figure 38. Red alder (SI: 65, high-density plantation, no treatment): Transitions of share of each GWMP100 factor's contribution along the HA

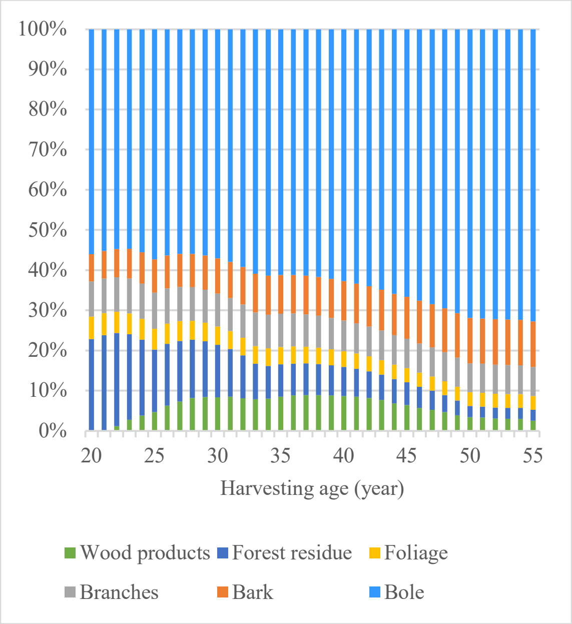


Figure 39. Douglas-fir (SI: 145): Transitions of share of each GWMP100 factor's contribution along the HA

Figure 40 and Figure 41 visualize the breakdown of GWMP100 related to wood products in two types, 'with emissions' and 'without emissions'. The highest GWMP100 without emissions in Red alder is provided by landfill. The particleboard's GWMP100 follows it, and the third is the lumber. Focusing on GWMP100 without emissions, the particleboard is close to the landfill. The emissions from manufacturing particleboard substantially drop its GWMP100 value with emissions. The paper and recycled paper also produce larger emissions, making its GWMP100 with emissions negative. That means manufacturing and recycling paper enhances global warming. Douglas-fir has a similar tendency in the GWMP100 of paper, landfill, and recycling. However, the big difference is the lumber, which is the highest in the group. The longevity gap between softwood lumber and hardwood lumber drives the difference in the lumber of the two species. While the carbon fraction in hardwood lumber decreases to 0.5 11 years after production and to 0.1 at 40 years, the fraction of hardwood lumber keeps more than 0.5 until 31 years and more than 0.1 until 128 years. Therefore, the carbon stays much longer in softwood lumber than hardwood lumber. It consequently gives GWMP100 of lumber a lower position in Red alder than Douglas-fir. The GWMP100 of particleboard is remarkable to compare. The emissions by producing particleboard from Red alder wood are less than Douglas-fir because of the high efficiency of manufacturing Red alder wood products by simultaneously producing co-products. It leads to less offset of GWMP with emission for Red alder's particleboard.

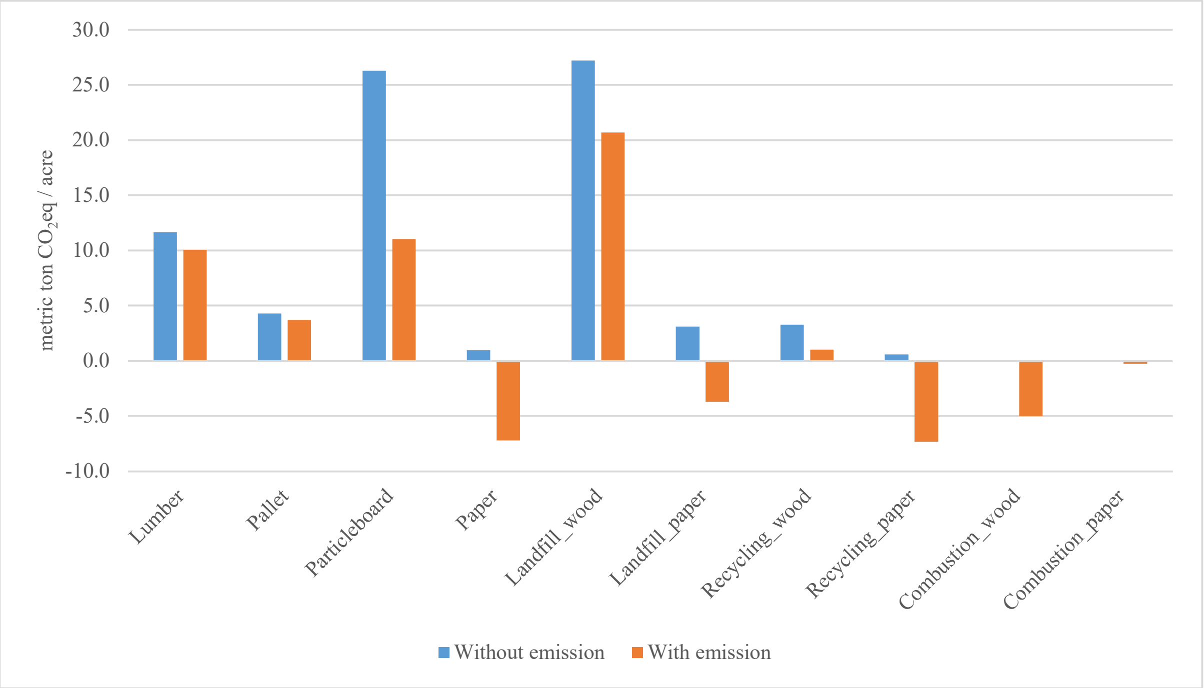


Figure 40. Breakdown of Red alder(site index: 65, harvesting age: 30, high-density plantation, no treatment): GWMP related to wood products

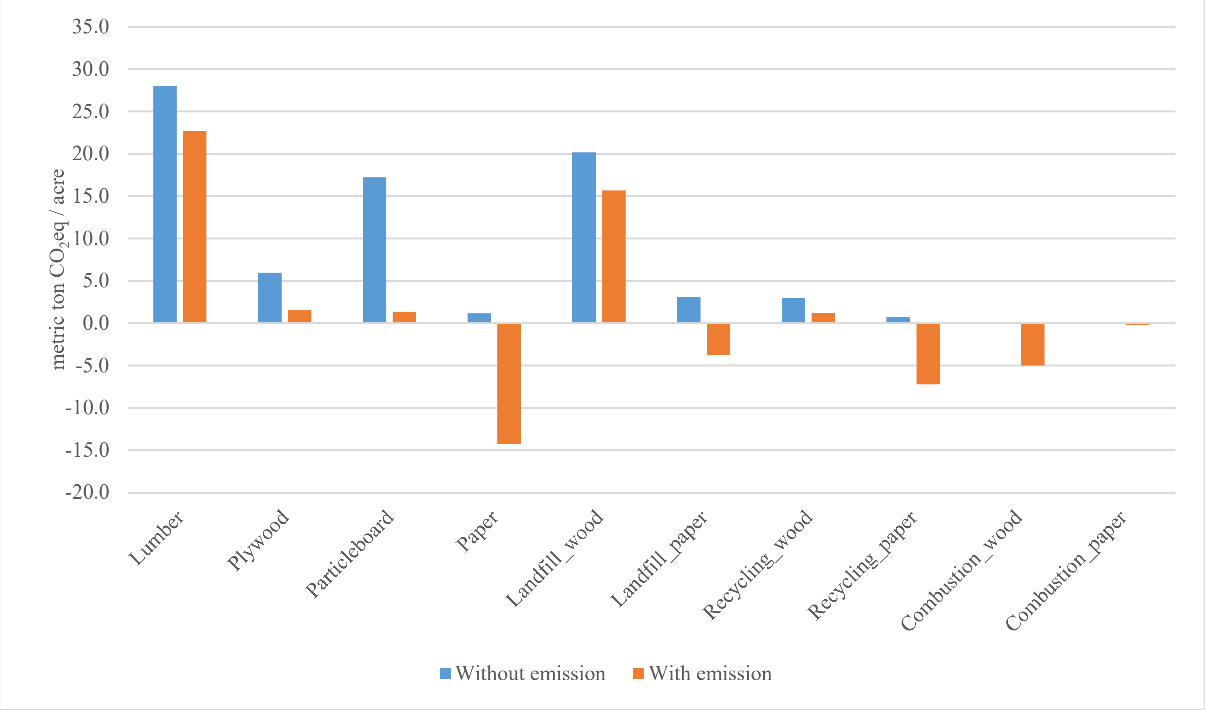
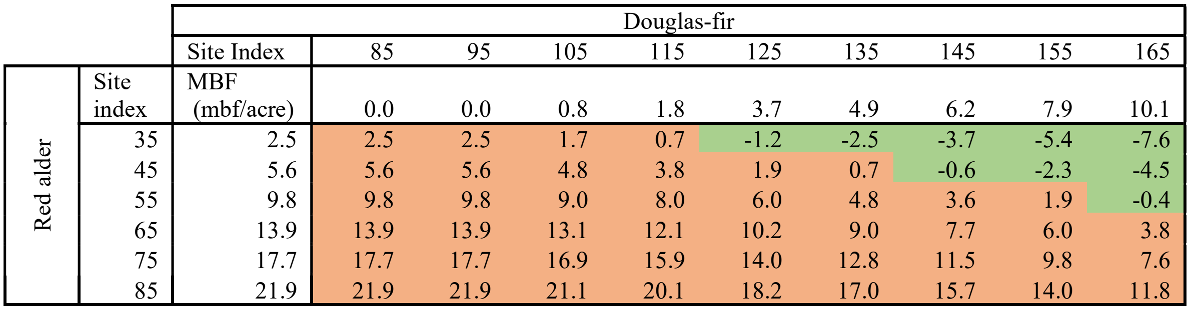


Figure 41. Breakdown of Douglas-fir (site index:145) GWMP related to wood products

As a result, the Red alder plantation is superior to Douglas-fir in the GWMP100 under short-term rotations, such as harvesting ages under around 30 years, when the harvesting age of Douglas-fir is the same. The analysis on the 25-year time horizon also indicates that Red alder is a better choice to sequestrate more carbon in the short term. The significant speed of growth in its juvenile stage and the higher ratio of merchantable log biomass than Douglas-fir contribute to those consequences. Hence, Red alder can play an essential role as an NCS in an environment that requires a rotation with short harvesting age, such as when small-diameter logs are in high demand, and increasing harvesting volume helps raise the profit of landowners. Table 17 shows the merchantable log volume for both species at the age of 30 years. Orange cells mean Red alder produces more merchantable volume in the corresponding area. According to Table 10, the landscape share of site index combination in orage cells in WESTERN WA is 99.7%, including site index: 95. It is predicted that Red alder plantations in ages under 30 years outstrip Douglas-fir from the perspective of merchantable log production since juvenile Red alder grows at a high rate. Hence, Red alder is a better option as NCS to mitigate global warming if producing more logs is vital, ignoring the difference in wood quality between the two species.

Table 17. Comparison of merchantable log volume at the age of 30 years



			Douglas-fir								
		Site Index	85	95	105	115	125	135	145	155	165
	Site index	MBF (mbf/acre)	0.0	0.0	0.8	1.8	3.7	4.9	6.2	7.9	10.1
Red alder	35	2.5	2.5	2.5	1.7	0.7	-1.2	-2.5	-3.7	-5.4	-7.6
	45	5.6	5.6	5.6	4.8	3.8	1.9	0.7	-0.6	-2.3	-4.5
	55	9.8	9.8	9.8	9.0	8.0	6.0	4.8	3.6	1.9	-0.4
	65	13.9	13.9	13.9	13.1	12.1	10.2	9.0	7.7	6.0	3.8
	75	17.7	17.7	17.7	16.9	15.9	14.0	12.8	11.5	9.8	7.6
	85	21.9	21.9	21.9	21.1	20.1	18.2	17.0	15.7	14.0	11.8

Note: Conditions of the plantations is no thinning and no post plantation treatment.

Considering the improvement in the potential for Red alder to mitigate global warming by promoting carbon storage, finding a sustainable way to utilize forest residue for the long term is an idea, especially for branches. Branches contribute to GWMP100 relatively two times higher than that of Douglas-fir. Forest residue is commonly left on the ground or burned instead of utilized, as collecting those is not economically sustainable. In addition, replacing paper manufacturing with producing other longer functional lifetime products, such as biochar, which can last more than 100 years, is one substitute option.[47] If we can provoke a demand for alder-derived biochar, CS produced by Red alder products has a high chance of expanding. Though it is not only for forestry areas, innovating techniques to reduce emissions released through manufacturing is also a considerable way.

3.1.4 *The uncertainty analysis on the GWMP*

This section describes uncertainty in the dynamic LCA analysis to assess the reliability of the GWMP estimations. The points of uncertainty are product mix and unit emissions of products in Red alder. This study uses the red alder product mix based on the average of three mills investigated by CINTRAFOR (2022). [18] Changing product mix leads to different amounts of production in wood products. Table 18 shows the average product mix used in this analysis and three cases surveyed in the report. Euclidean distance between the average dataset and each mill dataset illustrates that the data of Mill C diverge most from the average dataset since it has the largest value of three.

Table 18. Report data of Red alder product mix

Product	Average	Mill A	Mill B	Mill C
Lumber	29.1%	28.6%	28.0%	32.4%
Pallet	10.7%	10.6%	10.3%	12.0%
Chips	35.3%	35.8%	35.2%	34.7%
Hog Fuel	13.2%	13.9%	15.4%	7.5%
Sawdust	11.6%	11.2%	11.1%	13.4%
Euclidean distance (from Average)	0.000	0.011	0.026	0.069

Note: This data is based on CINTRAFOR (2022). The names, Mill A, Mill B, and Mill C are used to show they are different data set each other. The average product mix is based on the sum of production volume in three mills. Therefore, it does not match with the average of percentages in three mills data set. Euclidean distance indicates the discrepancies between Average data set and each mill data set.

The GWMP100 with the Mill C product mix is 136.2 t CO_2 / acre, which is 3% bigger than the one with the average product mix since Mill C has a higher share of lumber, sawdust, and pallet production and lower Chips and Hog fuel production. The extended longevity of lumber and pallet increase the carbon storage benefit. The Mill A and the Mill B product mix does not differentiate GWMP100 from the average value. (Table 19)

Table 19. GWMP with each product mix (Unit: t CO_2 / acre)

Average	A	B	C
131.6	130.7	130.1	136.2

Emissions of production is also based on the report. There is a range of emission in each product and in each GHG type. Table 20 indicates the average, the maximum, and the minimum emission values with each coefficient of variation that quantifies the data variability. According to the table, lumber production emissions have the widest range in both CO_2 and CH_4 emissions.

Table 20. Survery data of emissions (Unit: kg / kg of product)

Product	GHG	Average	Max	Min	CoV
Lumber	CO_2	0.076	0.093	0.065	0.164
	CH_4	0.000	0.000	0.000	0.159
Pallet	CO_2	0.076	0.093	0.066	0.162
	CH_4	0.000	0.000	0.000	0.156
Miscllaneou (Particle board)	CO_2	0.429	0.433	0.420	0.014
	CH_4	0.002	0.002	0.002	0.007
Paper	CO_2	1.249	1.252	1.247	0.002
	CH_4	0.003	0.003	0.003	0.001
Recycling Particleboard	CO_2	0.328	0.333	0.320	0.019
	CH_4	0.002	0.002	0.002	0.007
Burining Hog fuel	CO_2	0.151	0.167	0.141	0.077
	CH_4	0.0004	0.0004	0.0004	0.063

Note: “CoV” means coefficient of variation.

The GWMP factored in the set of the maximum emissions results in 130.8 t CO_2 / acre, and the GWMP with the sed of the minimum emissions is 132.1 t CO_2 / acre. (Table 21) The differences from the GWMP based on the average emissions are both less than 1 t CO_2 / acre. The variation of emisssions does not significantly impact the GWMP results.

Table 21. GWMP with each emission (Unit: t CO_2 / acre)

Emission		
Average	Maximum	Minimum
131.6	130.8	132.1

3.2 NET PRESENT VALUE

Figure 42 and Figure 43 indicate the NPV with the 5% discount rate. Considering Red alder, Plantation in site index: 85 and 75 only can attain a positive NPV meaning economically profitable. The share of the two site indexes in WESTERN WA is 46.92%, according to Table 10. Though this study does not estimate NPVs of site index:95, plantation of site index:95 presumably has positive NPVs as a larger site index has more NPVs. Thus, the total proportion of site indices with positive NPVs is 48.28%. Half of the plantation area can yield positive NPVs. The NPVs in site index: 85 are the highest among all harvesting ages, with the most significant number at the youngest harvesting ages, 20 years. The tendency of NPVs in site index: 75 climbs at first, but it also continues to drop after the point of 24 years ($109/acre). The harvesting age of 28 years is the last one in which NPV is above zero. The range of change is the highest in the site index: 85, dropping approximately $600 per acre from the begging to the end.

NPVs of Douglas-fir display significantly different characteristics from Red alder's ones. They keep growing until longer harvesting ages. Plantations with more than the site index:125 can produce positive NPVs. The apexes of site indexes with positive NPVs are placed between 45 and 50 years of harvesting age, while Red alder's NPVs are the largest in the first 10 ages. Following Table 10, the area with site index of more than 125 occupies 94.24% of the WESTERN WA landscape. It means Douglas-fir has the doubled possibility of gaining lucrative plantation compared to Red alder.

Additionally, the Douglas-fir plantation in site index:165 attains $1406/acre at the age of 47 years, which is roughly three times larger than the highest NPV in Red alder, $ 501/acre at the age of 20 years in site index: 85. Red alder cannot exceed Douglas-fir in NPV even if summing values of three times cycles. Comparing two species in the largest and the second largest site index combination, the utmost NPVs are -$263/acre for Red alder (site index: 65), $109/acre for Red alder (site index:75), and $647/acre for Douglas-fir (site index:145). Douglas-fir still much excels than Red alder.

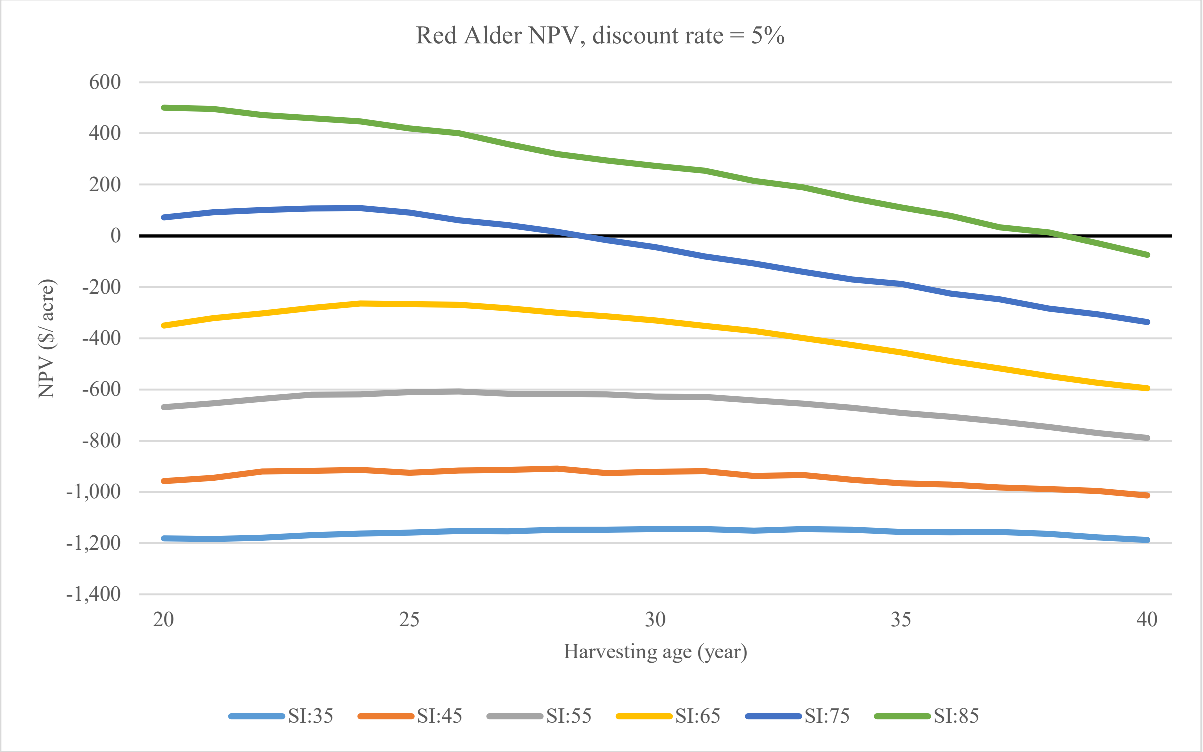


Figure 42. NPV of Red alder (high-density, no treatment) with discount rate: 5% in different site indices

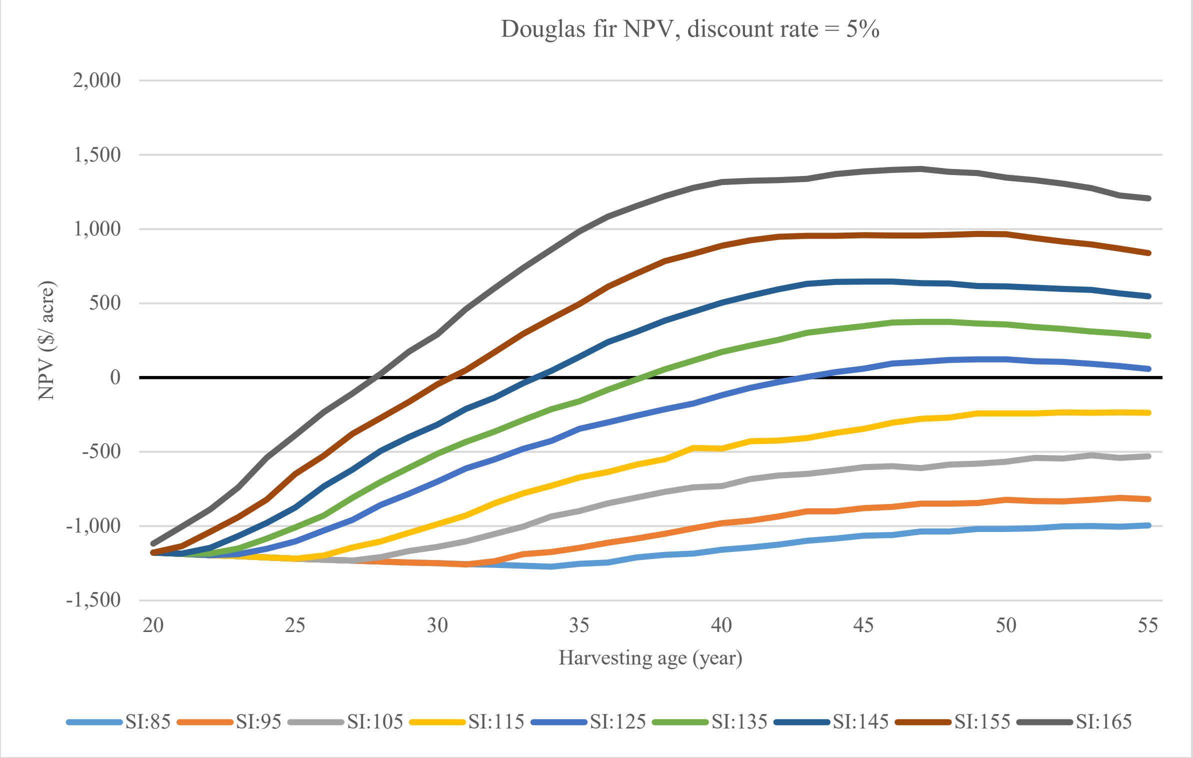


Figure 43. NPV of Douglas-fir with discount rate: 5% in different site indicies

Figure 44 and Figure 45 illustrate the transition of NPVs with the 7% discount rate following harvesting ages. For Red alder side, site index:85 has the only condition that Red alder can generate positive numbers in NVPs at the age of 20 and 21, with the highest value of $52/acre at the age of 20 years. The share of site index:85 in the landscape is 13.02% based on Table 10. Site index: 75 changes its tendency into decreasing without increasing among all harvesting ages.

Considering Douglas-fir, site index:165 is the only one that can produce positive NPVs, with the highest number at $114/acre at the age of 39 years. The percentage of site index:165 in the WESTERN WA landscape is 0.14%. That is totally smaller than Red alder's possibility of attaining positive NPVs. Changing the discount rate from 5% to 7% results in Red alder outstripping Douglas-fir in moneymaking, though the highest NPV of Douglas-fir is 2.2 times greater than Red alder. The span of harvesting age where Douglas-fir's NPV becomes the peak in each site index condition moves to between 40 and 45. It means younger harvesting age is preferable in the case of prioritizing NPV. The difference between both the highest NPV values diminishes. While Douglas-fir at site index:165 reaches the peak of NPV at the age of 39 years, Red alder at site index:85 makes out the peak at the age of 20 years. Hence, Red alder cannot attain a larger NPV for 40 years by finishing two cycles of rotation than Douglas-fir.

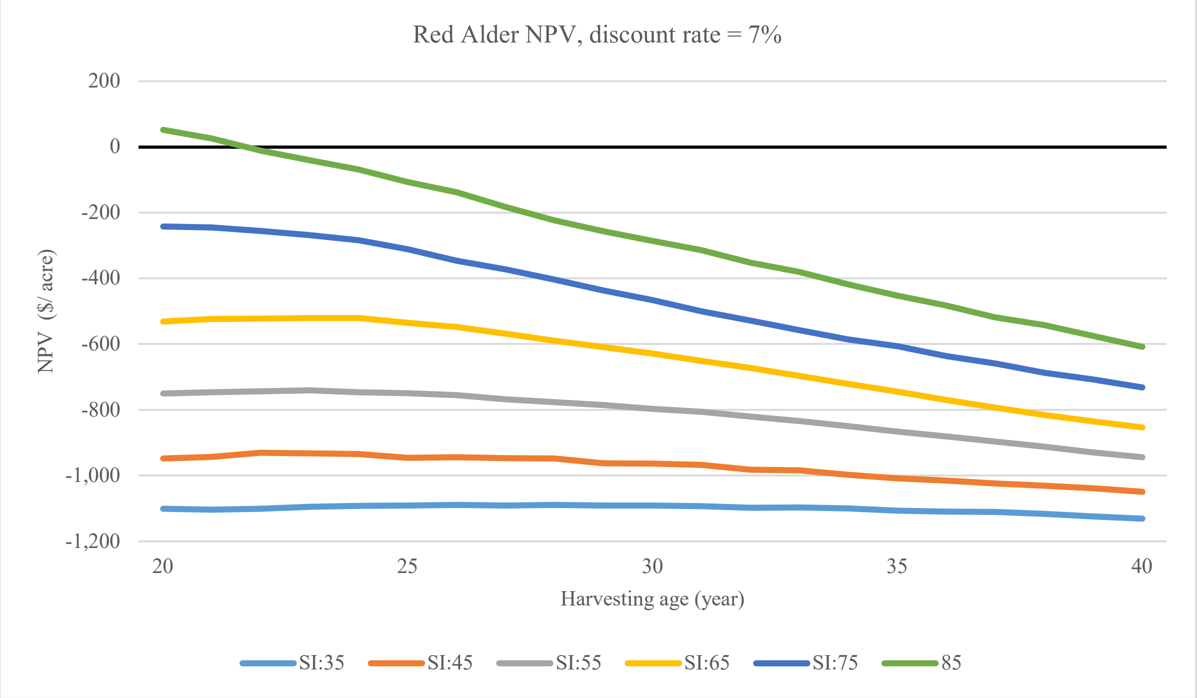


Figure 44. NPV of Red alder (high-density, no treatment) with discount rate: 7% in different site indicies

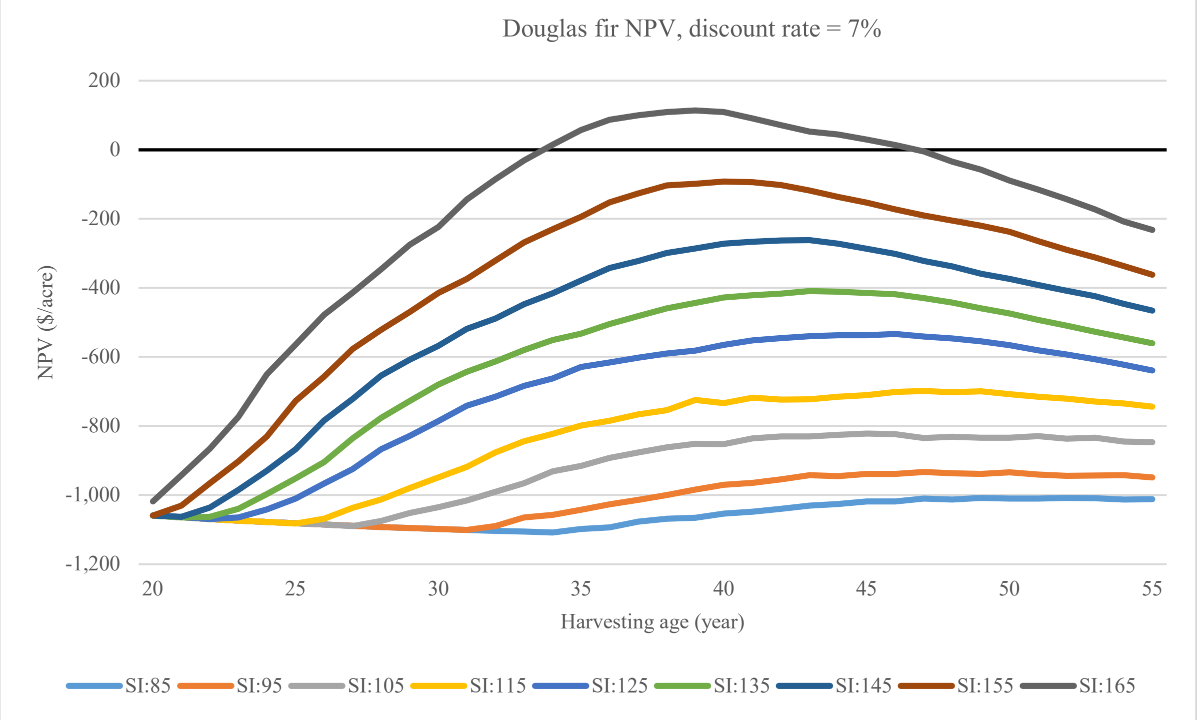


Figure 45. NPV of Douglas-fir with discount rate: 7% in different site indicies

The reason why NPV of Red alder in earlier harvesting ages tends to be higher than those in larger ages is attributed to slighter growth of distribution of superior log grade compared to Douglas-fir. Figure 46 illustrates the log-grade distribution of Red alder along harvesting ages. The grade of 4 saw dominants the most in any age, though the share of 2 saw and 3 saw marginally grow. On the contrary, log grade distribution in Douglas-fir notably change as harvesting age increase. (Figure 47) The 2 saw expands its share, while the percentage of 3 saw and 4 saw a decrease. It creates the situation that the unit price of Red alder is also challenging to increment. Figure 48 depicts transitions of unit prices in Red alder. Though site index: 85, 75, and 65 for Red alder increase their unit prices, the rest of the site indexes are almost stable. The unit price of Douglas-fir grows along harvesting ages, though the growth rate becomes higher as the site index grows. (Figure 49) The power of the discount rate to drop the NPVs is enhanced as the harvesting age increases.

Therefore, if the harvesting revenue cannot grow over the influence of the discount rate, the NPVs decrease along the harvesting age up. The low growth rate of unit price for Red alder leads to fewer NPVs at later harvesting ages, in distinction to Douglas-fir.

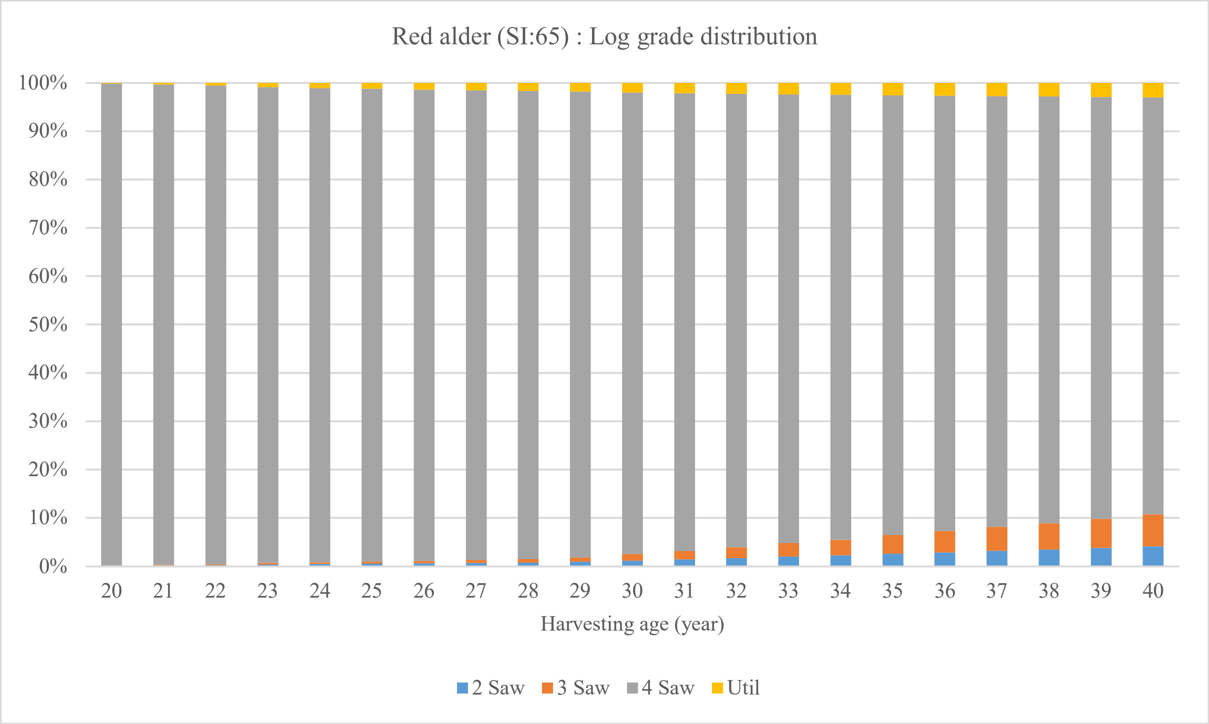


Figure 46. Log grade distribution of Red aler (SI:65, high-desnity, no treatment)

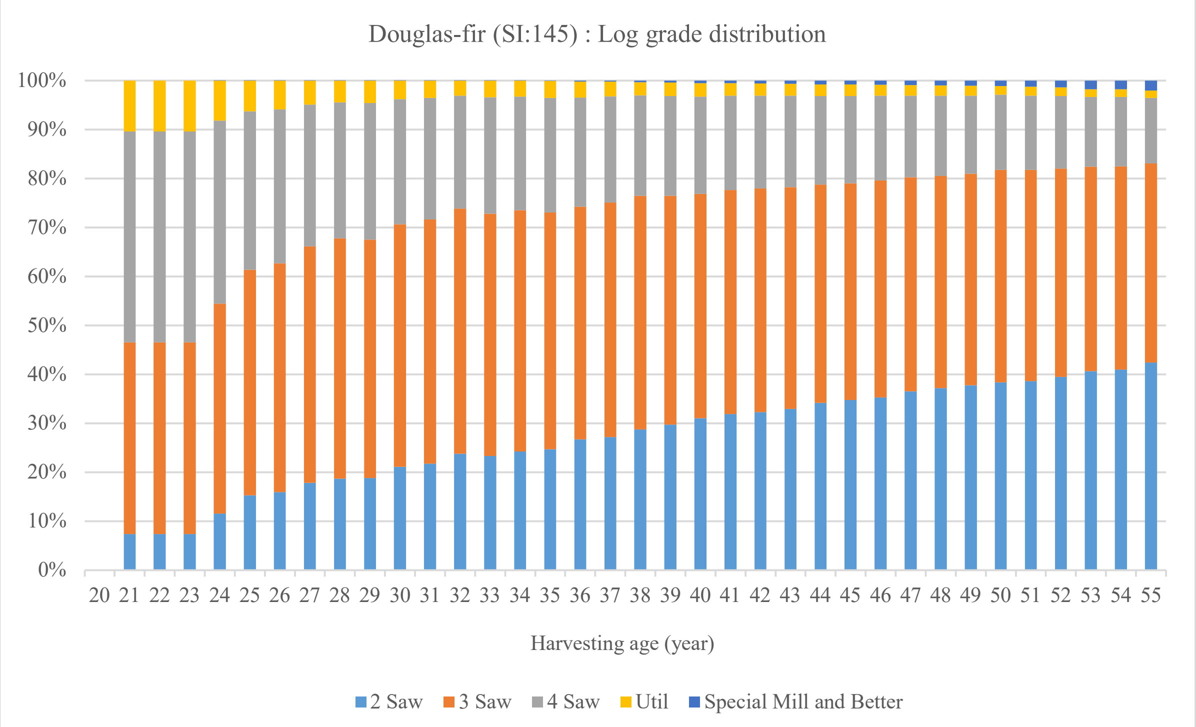


Figure 47. Log grade distribution of Douglas-fir (SI:145)

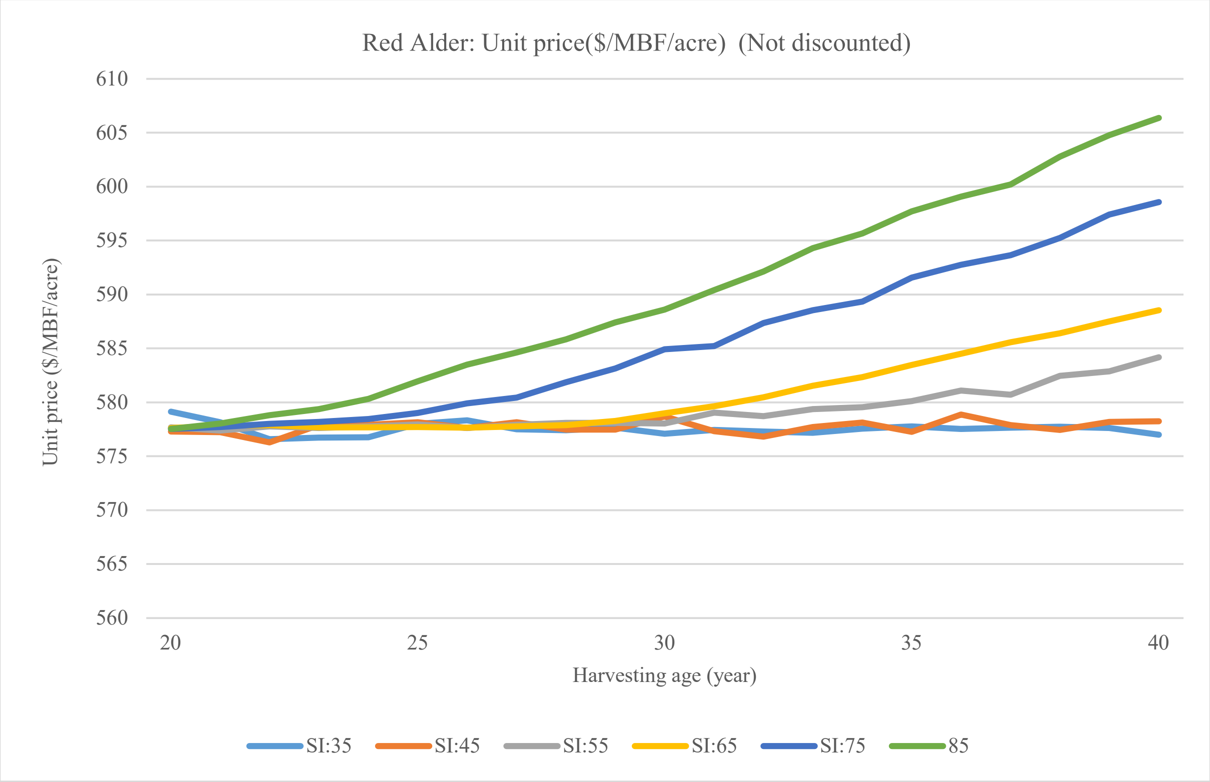


Figure 48. Unit price of Red aler (SI:65, high-desnity, no treatment) in different site

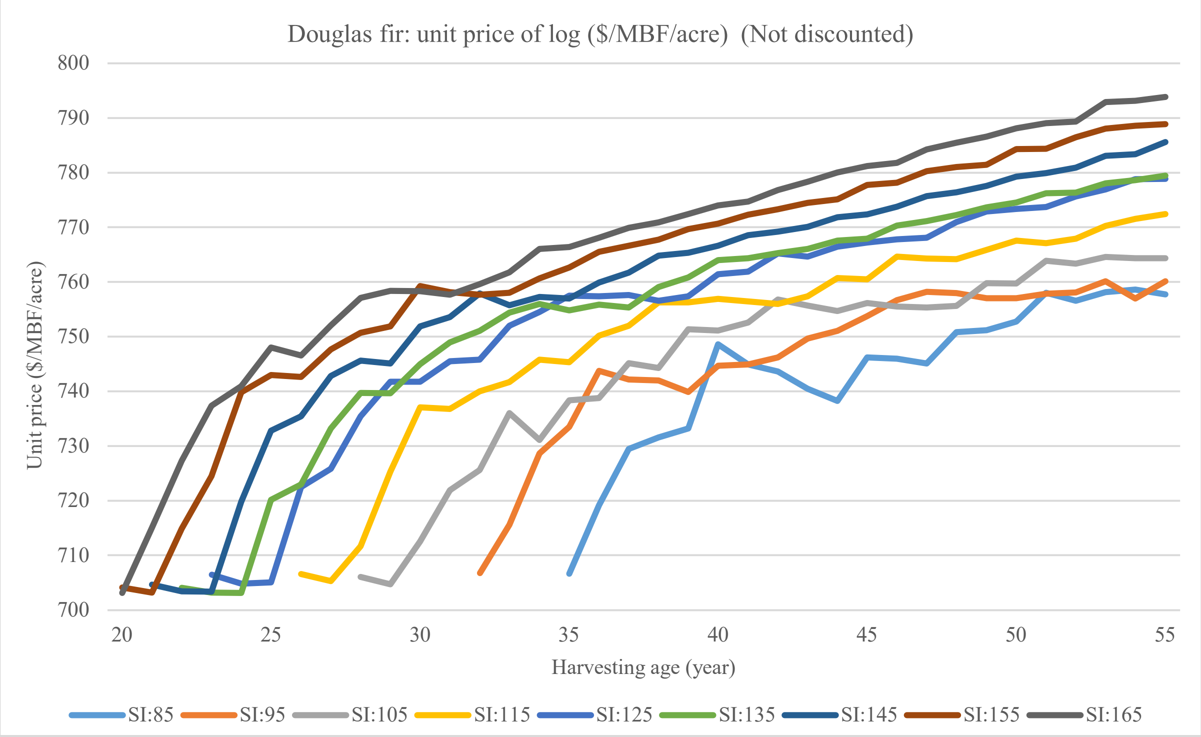


Figure 49. Unit price of Douglas-fir (SI:145) in different site indices

In the next step, this study compares GWMP100 and NPV by standardizing both values to spot optimal harvesting ages depending on different prioritization. This research uses a combination of site index:65 for Red alder and site index:145 for Douglas-fir, and site index:75 for Red alder and site index:145 for Douglas-fir. Those two combinations have the first and the second largest share in the WESTERN WA landscape. In addition, site index:65 does not make any positive NVP in the cases of this study, unlike site index 75. Site index 75 can generate results for optimal harvesting age with positive NPV for Red alder plantations.

Figure 50 indicates the standardized NPV and GWMP100 for Red alder in the site index:65 and high-density conditions without thinning. The grey line represents the total of NPV and GWMP100. The NPV starts to decline after the age of 24 year, and the growth of GWMP100 last even though it's speed significantly drops after the age of 34 years. The harvesting age of 40 year gain the greatest GWMP100. The highest value of standardized NPV and GWMP sum is at the harvesting year 33. The case of site index:75 is similar to that of site index:65. (Figure 51) Nevertheless, the decrease rate of NPV after the age of 24 is larger, which lowers the sum of NPV and GWMP100 between 25 and 33 years. Consequently, the highest sum of the two is gained at the harvesting age 25 years. The NPV reaches the apex at the harvesting age of 24, same as the case of site indee:65. The harvesting ages below 27 years gain positive NPVs. Hence, the age of 25 is optimal for balancing NPV and GWMP100 with gaining profit from plantation management. Figure 52 displays shifts of NPV and GWMP100 in the Douglas-fir plantation with the site index: 145. It shows a remarkably more prolonged increase of NPV than Red alder until harvesting age 50 years and a fluctuation after that point. The peak value of NPV is at 46 years, and the topmost of GWMP100 is 54 years. The harvesting age of 50 years attains the supreme sum of standardized NPV and GWMP100 within a span of ages with above-zero NPV.

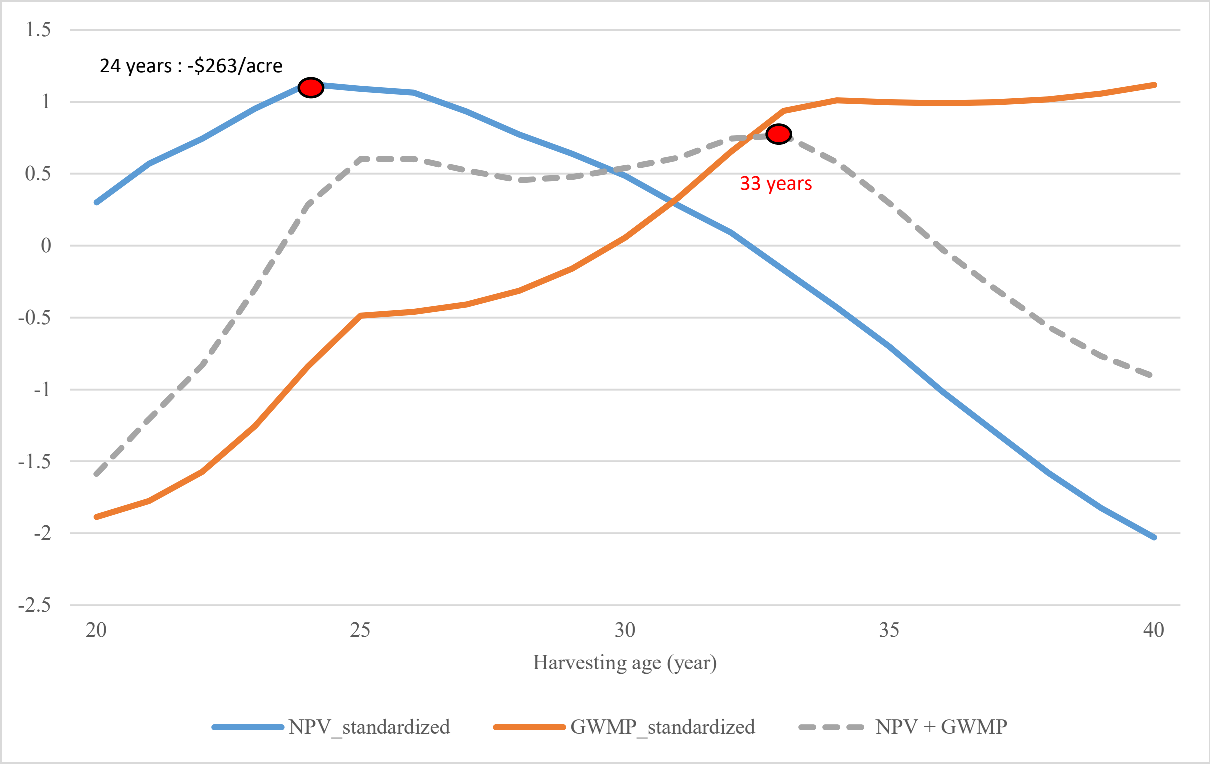


Figure 50. NPV and GWMP100 of Red alder (SI:65, high-density, no treatment) with discount rate: 5%

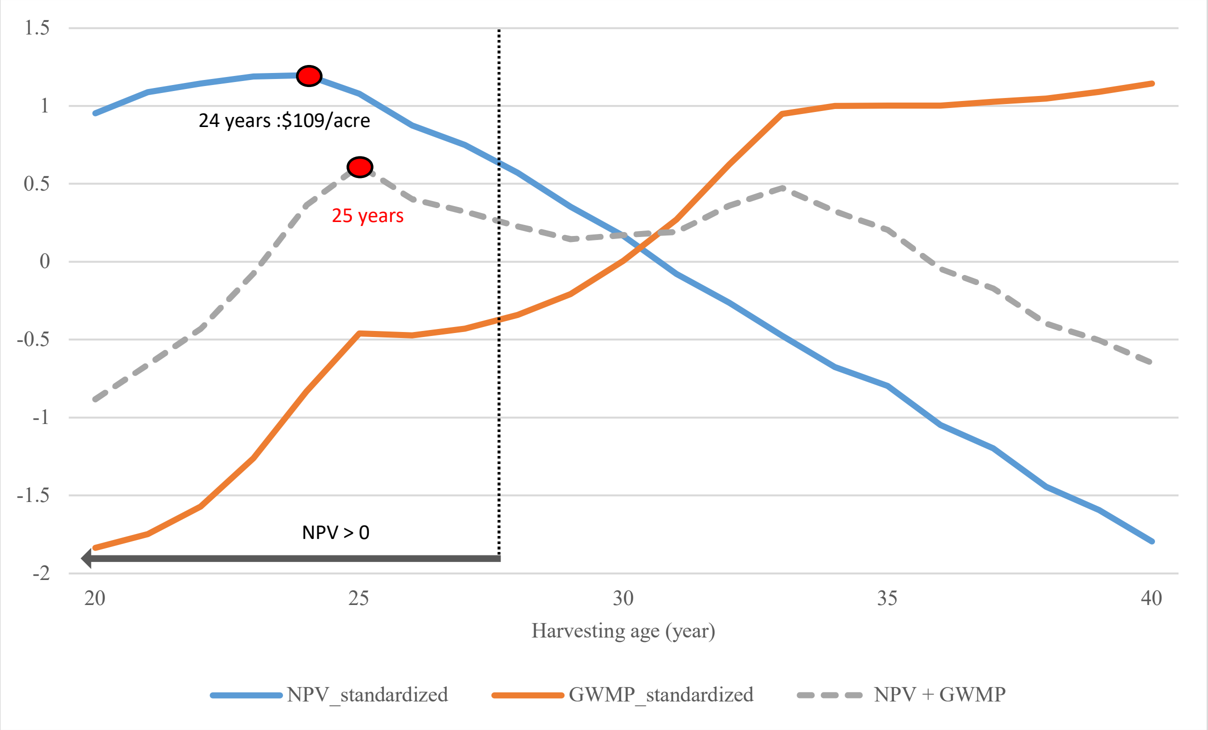


Figure 51. NPV and GWMP100 of Red alder (SI:75, high-density, no treatment) with discount rate: 5%

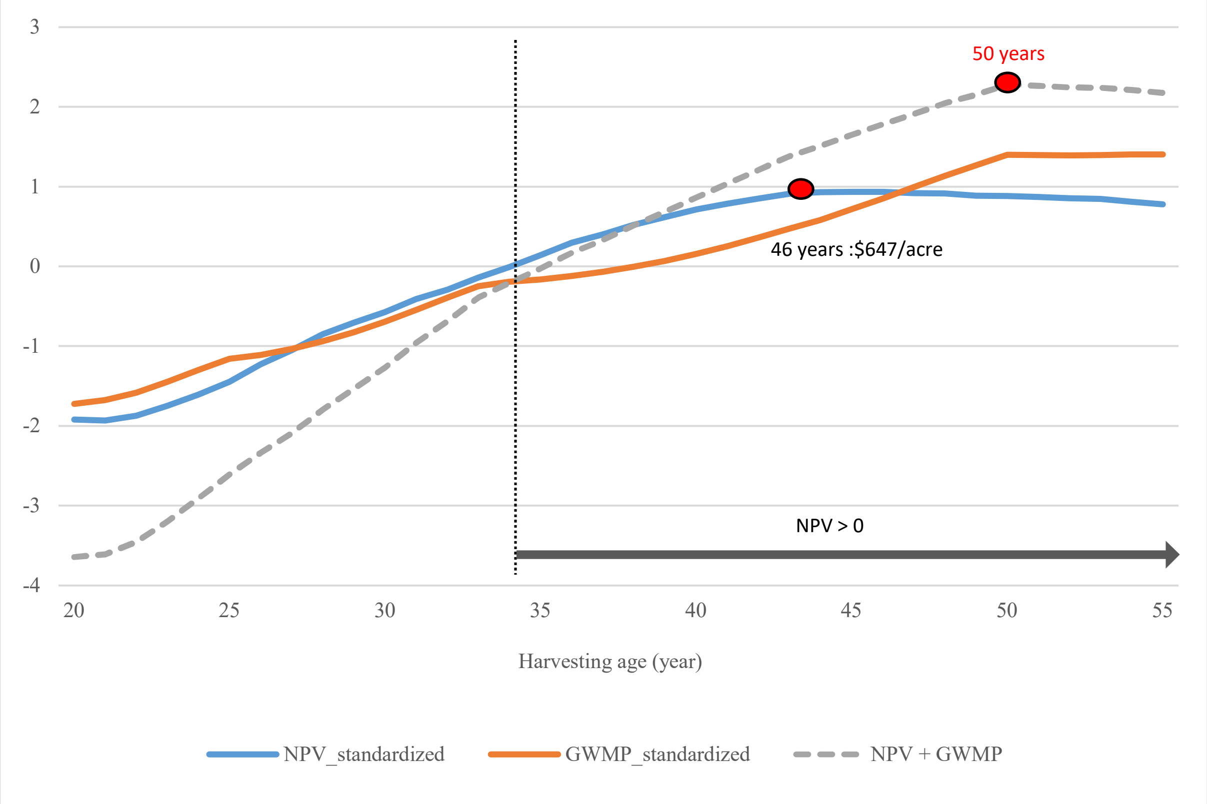


Figure 52. NPV and GWMP100 of Douglas-fir (SI:145) with discount rate: 5%

Figure 53 and Figure 54 illustrate the cases of site index 65, and site index 75 in the discount rate 7%, respectively. They show a less increase during the early harvesting ages under 25 years in NPV. The tops are at 23 years for NPV, 40 years for GWMP100, and 25 years of the total. The optimal age of the total for site index: 65 moves to a much earlier age compared to 33 years of the case with a 5% discount rate. In the case of site index:75, the apexes are at 20 years for NPV, 40 years for GWMP100, and 25 years for the sum of the two. The beginning of the range of the harvesting ages is the most preferable for NPVs, while GWMP100 is maximized at the most extended harvesting age.

Figure 55 shows the case of Douglas-fir (site index:145) with the 7% discount rate. The optimal age to maximize each value is at 43 years for NPV, 55 years for GWMP100, and 50 years for the total of NPVs and GWMP100. The apex of NPV is earlier by 2 years, and the decrease rate of NPV after the peak is steeper than the case with the 5% discount rate. GWMP100 has a close tendency to the previous one. It results in the less highest value in the sum of the standardized two.

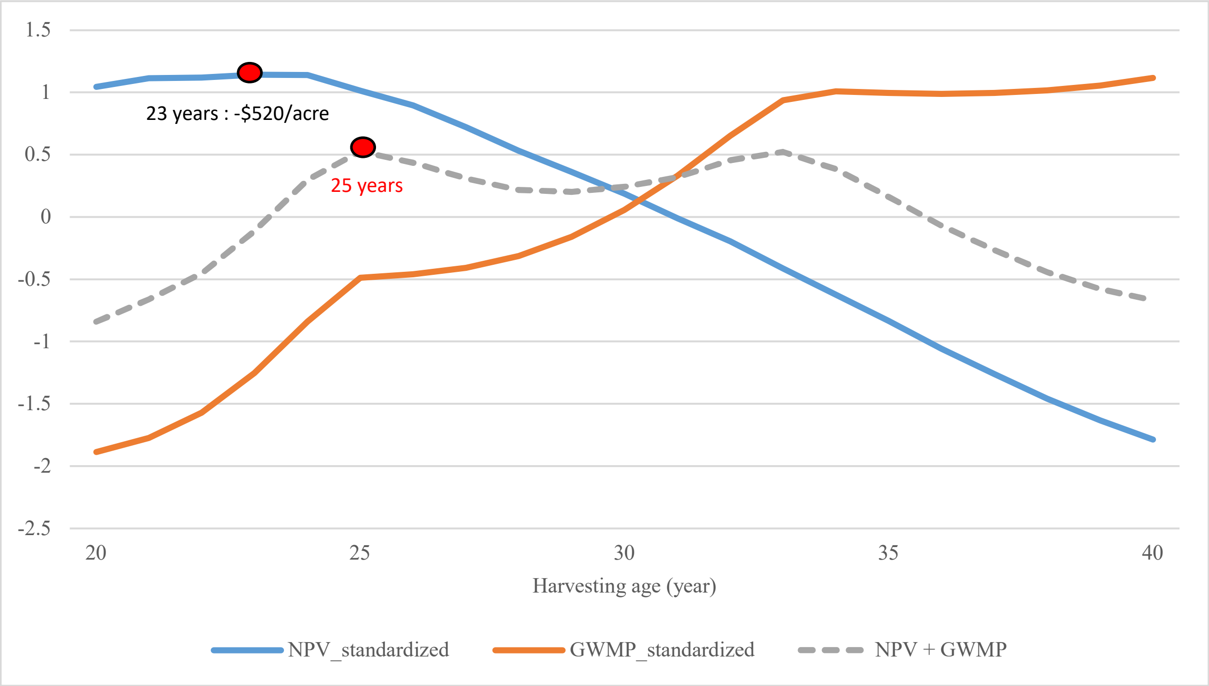


Figure 53. NPV and GWMP100 of Red alder (SI:65, high-density, no treatment) with discount rate: 7%

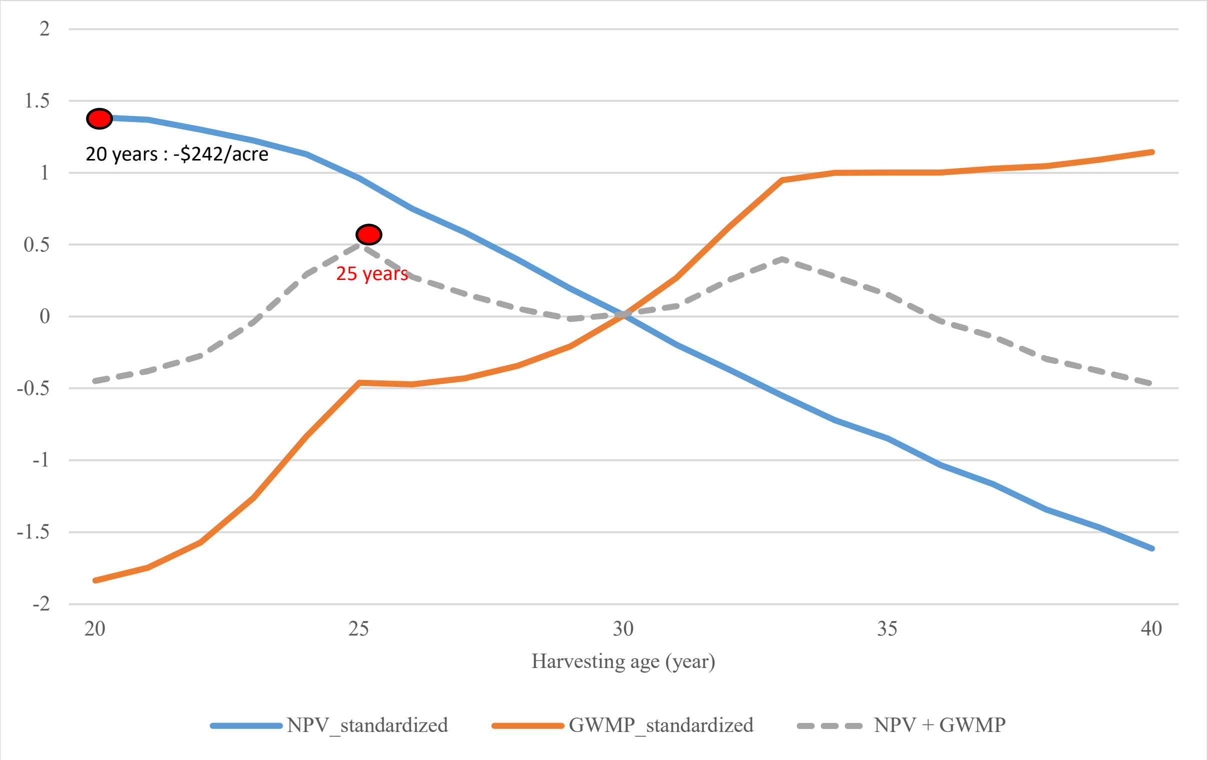


Figure 54. NPV and GWMP100 of Red alder (SI:75, high-density, no treatment) with discount rate: 7%

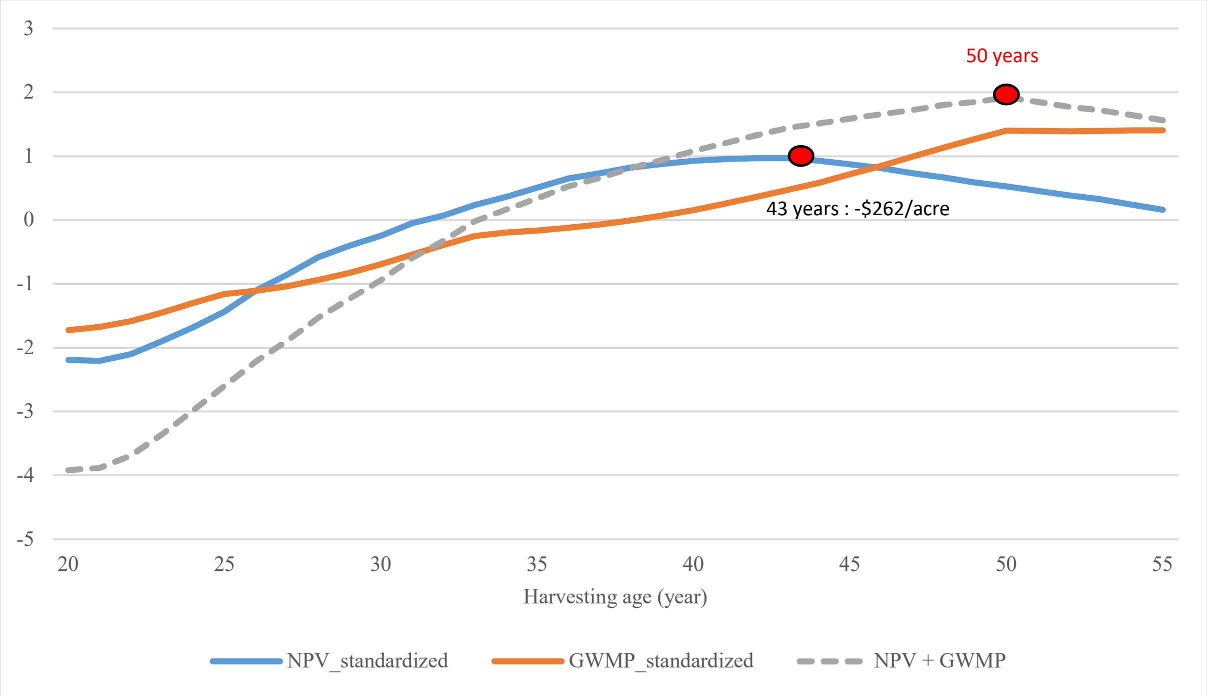


Figure 55. NPV and GWMP100 of Douglas-fir (SI:145) with discount rate: 7%

Summing up the results, Table 22 indicates the optimal harvesting ages in different conditions. The case prioritizing GWMP leads to maximizing harvesting age for both species. The optimal age for NPVs Red alder is a relatively earlier harvesting age of less than 25, while that of Doulas-fir is a later harvesting age of more than 40. The balanced optimal ages for both factors are the middle of those optimal ages. Considering the case with a 5% discount rate, the site index:75 for Red alder, and the site index: 145 for Douglas-fir have the span of harvesting ages enabling plantations to generate positive NPVs. The optimal age for the total of two factors within the rage of positive NPVs is the same as the age not considering positive NPVs.

Table 22. Optimal harvesting age in different discount rates (unit: year)

Prioritizing	Red alder (SI:65)		Red alder (SI:75)		Douglas-fir (SI:145)	
	5%	7%	5%	7%	5%	7%
GWMP	40	40	40	40	54	54
NPV	24	23	24	20	46	43
NPV + GWMP (any NPV)	33	25	25	25	50	50
NPV + GWMP (NPV > 0)	-	-	25	-	50	-

The balanced optimal harvesting age without losing profitability of Rred alder in site index:75 is half that of Douglas-fir in site index:145 when the discount rate is 5 %. The NPV is $109/acre for Red alder, and $647/acre for Douglas-fir, respectively. Though the Red alder plantation with 25 years of harvesting age repeats twice during one cycle of Douglas-fir plantation with 50 years of harvesting age, Douglas-fir outstrips the doubled NPV of Red alder, $182/acre, in the second largest site index combination. Red alder plantation in site index: 65 does not produce any positive NPV even in the case of the 5% discount rate, though it consists of the site index combination with the highest share of landscape in WESTERN WA. The values of GWMP100 are 167 t CO_2eq/acre for Red alder (SI:75) at 25 years of harvesting age, 225 t CO_2eq/acre for Douglas-fir (SI:145) at 50 years of harvesting age, 146 t CO_2eq/acre for Red alder (SI:65) at 33 years of harvesting age whichi is optimal to take the balance in site index:65. Douglas-fir excels in GWMP. Harvesting at the age balancing GWMP and NPV (5% discount rate) results in Douglas-fir outperforming in both factors.

3.2.1 *Uncertainty analysis on the Net Present Value*

The Net Present Value calculation is factoring in several elements. One of the determining factors is log prices which influences the profit critically. This study did an uncertainty analysis on the Net present value by changing the log prices based on its fluctuations. Table 23 indicates the maximum and the minimum log prices depending on the types of logs during April 2022 and March 2023.[44] Following the above NPV analysis, the uncertainty analysis on NPV also focuses on the three site indices, 65 and 75 for Red alder, 145 for Douglas-fir.

Table 23. The maximum and the minimum log prices (Unit: $ / MBF)

Dougals Fir	Maximum	Minimum
SM and better	1018	845
2 Saw	963	730
3 Saw	865	666
4 Saw	790	561
Utility/Pulp	534	311
Red Alder	Maximum	Minimum
2 Saw	817	625
3 Saw	783	580
4 Saw	682	492
Utility/Pulp	293	203

Source: DNR(2023)

Figure 56, Figure 57, and Figure 58 illustrate the shift of NPV as the harvesting age increase. Red alder with site index:65 can attain positive NPV with the maximum log prices, though the average log prices which were used for the NPV analysis in this study cannot make it. Although NPV in Red alder with site index: 75 with the lowest log prices indicates no profitability, the set of highest log prices lifts the NPV above zero except for harvesting ages less than 39. The highest NPV, in that case, is $526/acre, improved by $400/acre than the average log price case. While the elevation width and the descent width between the NPV in different log price cases are almost constant in both site indices of Red alder, those of Douglas-fir grow gradually. This inclination ascribes the change of merchantable log ratio with harvesting age in Douglas-fir. Earlier harvesting age, such as lower than 30 years, do not produce much volume of logs resulting in inducing revenue. Therefore, the difference among NPV in different conditions at the same harvesting age is minor. That also causes a small change in the beginning harvesting age at which the Douglas-fir plantations obtain positive NPV. The starting harvesting age, which enables plantations to obtain profitable values of NPV, is 37 years in the lowest log prices , followed by 34 years in the average price case and 32 years in the maximum price case.

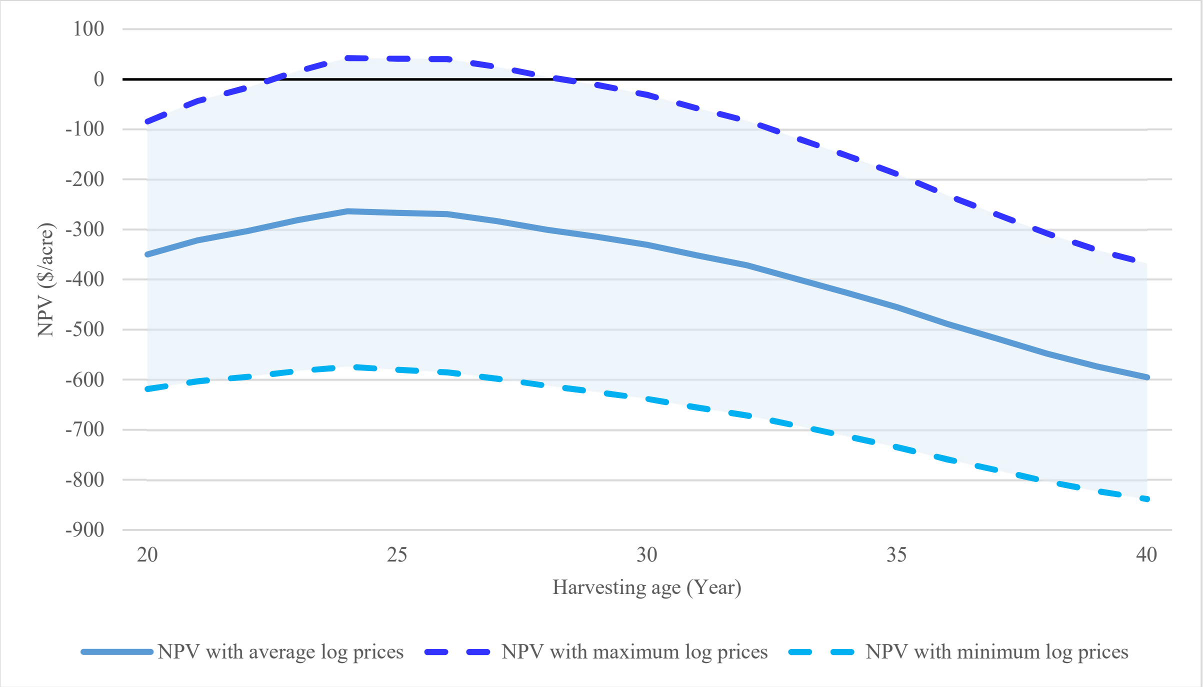


Figure 56. NPVof Red alder (SI:65, high density, no treatment) in different log price cases with the 5% discount rate

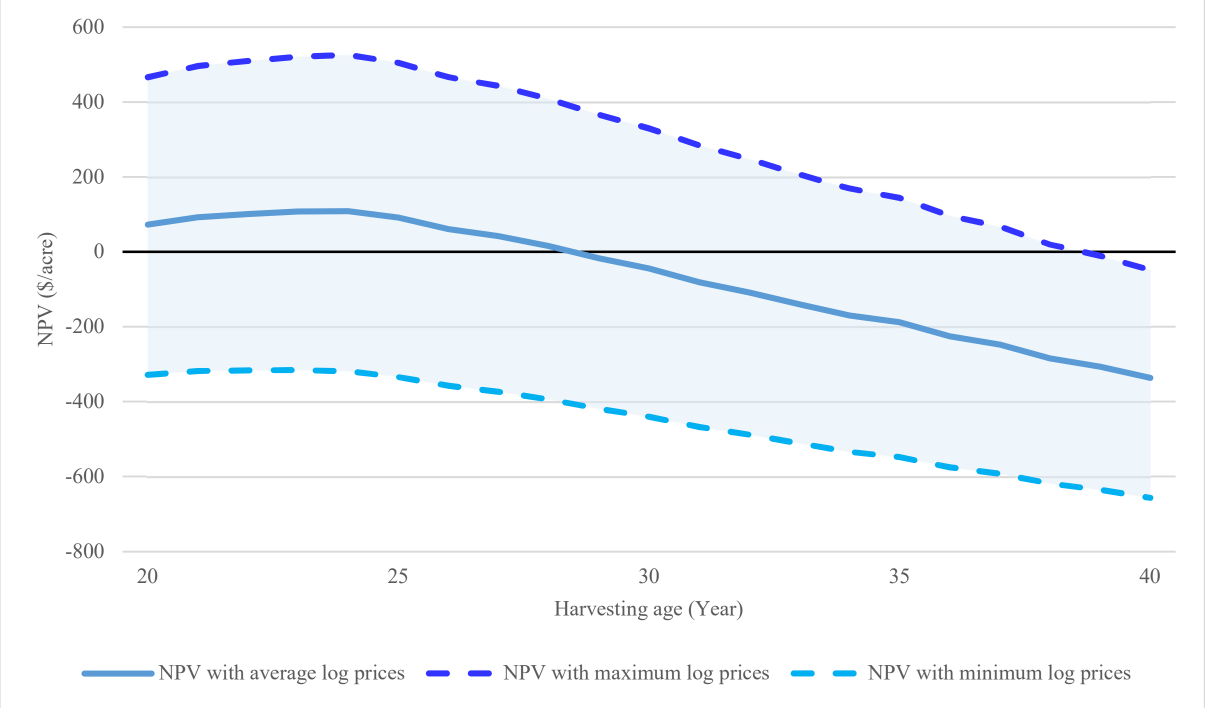


Figure 57. NPVof Red alder (SI:75, high density, no treatment) in different log price cases with the 5% discount rate

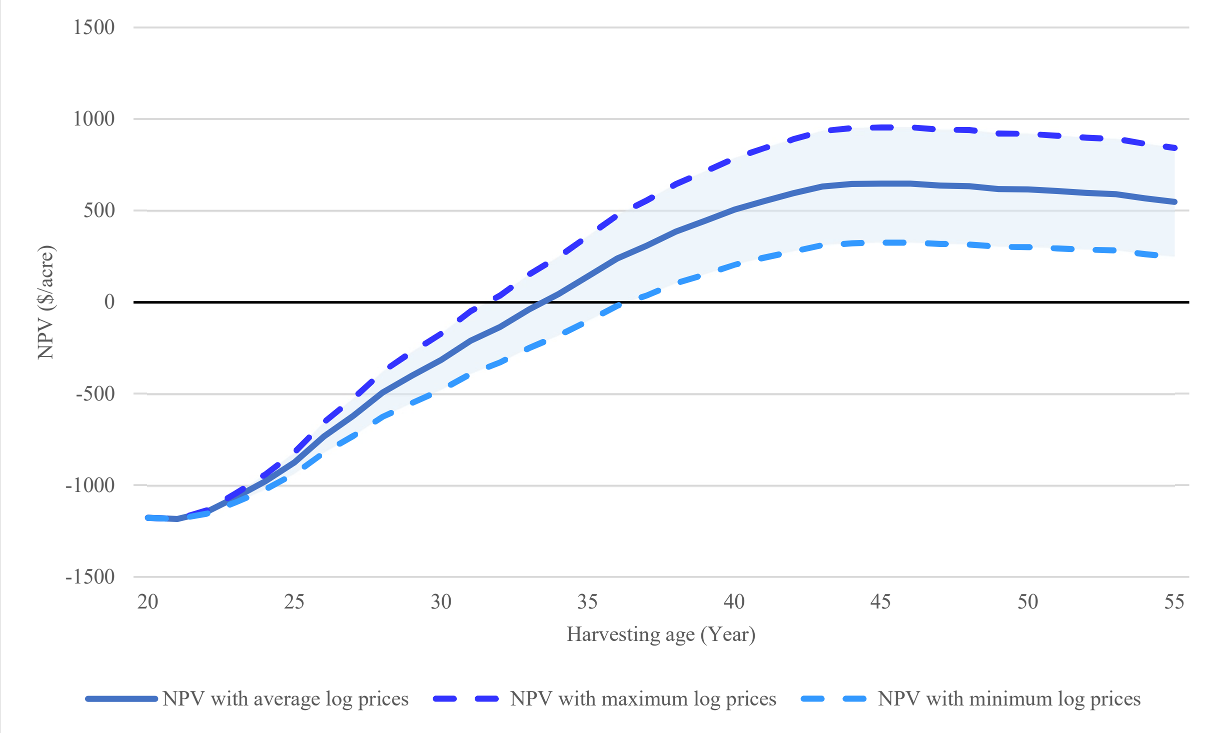


Figure 58. NPV of Douglas-fir (SI:145) in different log price cases with the 5% discount

Figures of NPV with 7% discount rate based on three log price scenarios shows that the width between the line of the average log price and the others gets narrower as the harvesting age increase. (Figure 59, Figure 60, Figure 61) The greater harvesting age is more influenced by the discount rate in diminishing the profit. Therefore, the more intense discount rate attribute to reduce the range of NPV outcomes depending on the various log pricing scenarios. Considering the Red alder plantation with the site index: 75, the maximum log price case enables the NPV results to be the amount above 0 between 20 and 22 years of harvesting age, though outcomes of Douglas-fir plantation at site index:145 are all below zero. The greatest value is $28.4/acre. Table 24 summarizes the total NPV outcomes in three log price scenarios. As this study mentioned, the positive NPV of Red alder at site index: 75 in the 7% discount rate condition is a significant change. While the Douglas-fir plantation at site index:145 is unprofitable at any harvesting age in the case of 7% discount rate analysis, the Red alder plantation at site index: 75 becomes viable when the maximum log prices are applied. This suggests that Red alder is a superior alternative if a landowner requires conducting profitable forestry management at the region with site index:75 for Red alder and site index:145 for Douglas-fir.

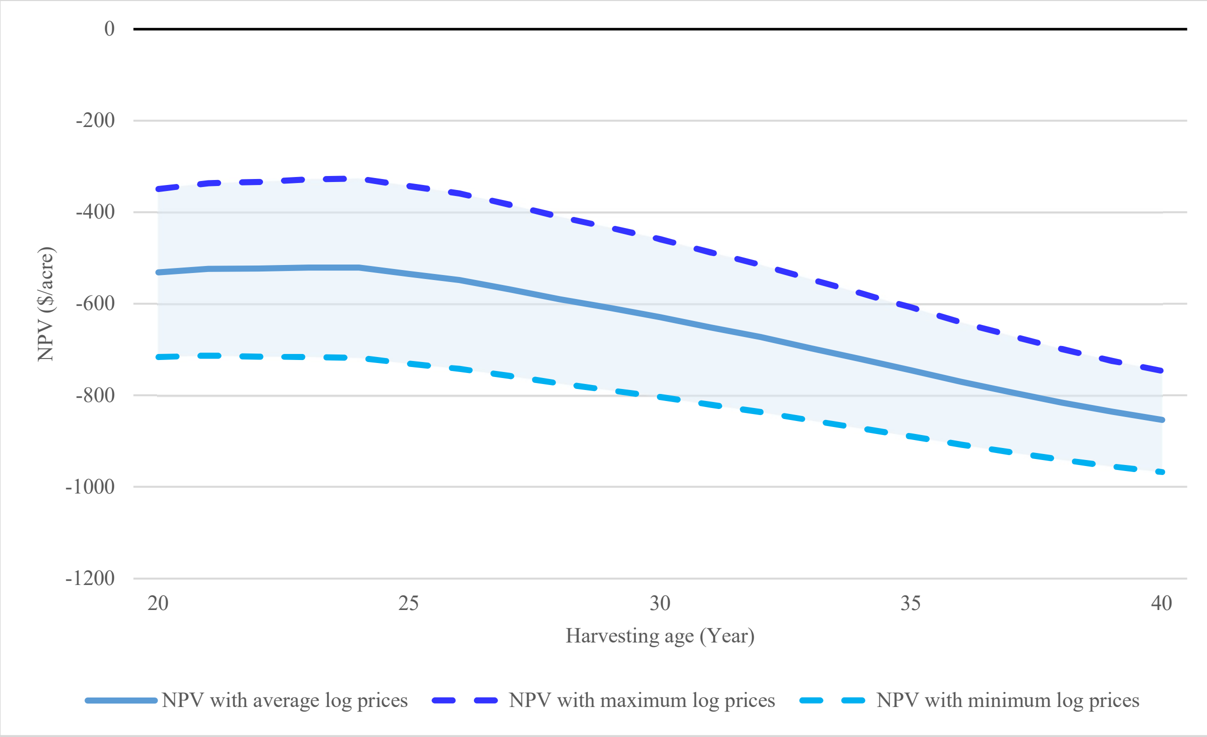


Figure 59. NPV of Red alder (SI:65, high density, no treatment) in different log price cases with the 7% discount rate

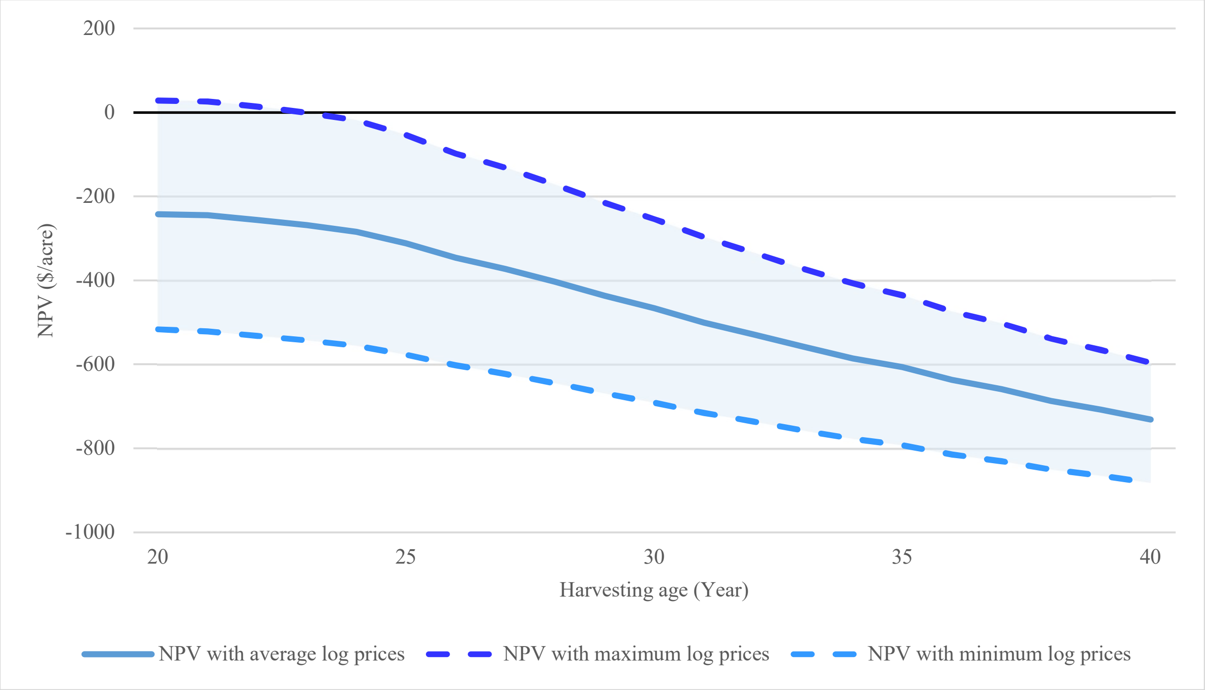


Figure 60. NPV of Red alder (SI:75, high density, no treatment) in different log price cases with the 7% discount rate

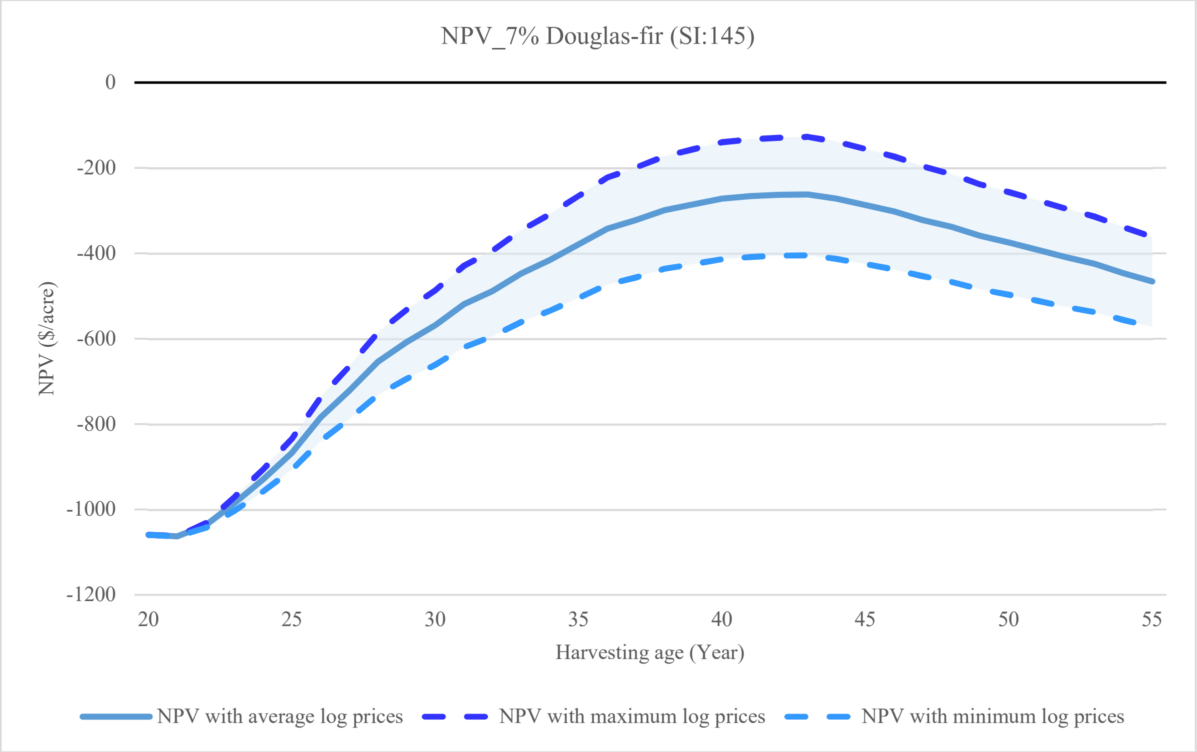


Figure 61. NPV of Douglas-fir (SI:145) in different log price cases with the 7% discount

Table 24. NPV depending on the different conditions (Unit: $ / acre)

		Red alder (SI:65)		Red alder (SI:75)		Douglas-fir (SI:145)	
		5%	7%	5%	7%	5%	7%
Log price	Average	-263.3	-520.5	108.8	-241.9	647.3	-261.9
	Maximum	42.5	-326.4	526.1	28.4	955.2	-127.0
	Minimum	-574.0	-712.9	-315.6	-516.3	325.6	-404.4

Optimal harvesting ages for maximizing NPV and for balancing NPV and GWMP in the maximum log pricing case propose two new ages. (Table 25, Table 26) The Red alder plantation at site index:65 can take a balance between NPV and GWMP at 26 years of harvesting age in the 5% discount rate condition within profitable forestry management. Similarly, for the Red alder plantation at site index:75, 25 years of harvesting age is ideal for balancing NPV and GWMP while maintaining profitability. Considering the case of the minimum log prices, the optimal harvesting ages for NPV become smaller than the case of the average price at Red alder plantation with site index:65 in 7% discount rate and Red alder plantation with site index: 75 in 5% discount rate. Other optimal ages are the same as the outcome from the standard analysis.

Table 25. Optimal harvesting age based on NPV with the maximum log prices (Unit: year)

Prioritizing	Red alder (SI:65)		Red alder (SI:75)		Douglas-fir (SI:165)	
	5%	7%	5%	7%	5%	7%
NPV	24	24	24	20	46	43
NPV + GWMP (any NPV)	33	25	25	25	50	50
NPV + GWMP (NPV > 0)	26	-	25	22	50	-

Table 26. Optimal harvesting age based on NPV with the minimum log prices (Unit: year)

Prioritizing	Red alder (SI:65)		Red alder (SI:75)		Douglas-fir (SI:165)	
	5%	7%	5%	7%	5%	7%
NPV	24	21	23	20	46	43
NPV + GWMP (any NPV)	33	25	25	25	50	50
NPV + GWMP (NPV > 0)	-	-	-	-	50	-

Chapter 4. FUTURE STUDIES FOR UNDERSTAND THE POTENTIAL OF RED ALDER AS NCS

This study focuses on only the rotation of single-specie plantations. However, other forest management options exist, such as mixed stands with Red alder and Douglas-fir and switching species after harvesting former plantations. They presumably differentiate GWMP from repeating the same pure plantation. Some research reported that Douglas-fir stands planted on a site where Red alder was previously planted had enhanced growth than repeated Douglas-fir stands. It implies that combining rotation of different species plantation has the potential to attain higher GWMP. Hence, studies to estimate GWMP for those cases help landowners to consider optimal management depending on objectives. But, ecological research to model forest stand development of those cases in different conditions is not sufficient currently, especially for research on the effect of Red alder's improving productivity of a site for conifers after planting. Hence, studies of forest ecology contributing to simulating forest growth in diverse types of plantations are integral for advancing GWMP research on wood products. Besides, this study does not incorporate a Red alder wood product mix change depending on diameter class. Diameter class composition is differed by harvesting ages. Adopting product mix for each diameter class significantly reflects the characteristics of merchantable logs in a certain harvesting age to GWMP results.

Furthermore, assessing the substitutional effects of wood products is unavoidable to cultivate the GWMP research on comparing Red alder and Douglas-fir. The substitutional effect occurs by substituting higher-emission materials with lower-emission materials. Wood products tend to release less manufacturing emissions than conventional building materials, such as concrete and steel. Replacing those with wood products for building leads to not using the high-emission material and preventing the difference in emissions of those. Wood products can support mitigating the environmental impact on global warming, not only by stored carbon but also substitution. This study did not consider the substitution effect. Hence, research on it is expected to understand the GWMP of two species more precisely.

This study clarifies that Red alder pure plantation can store carbon more than Douglas-fir in shorter harvesting rotation. Enlarging the ability of Red alder as NCS needs to increase the demand of Red alder woods in the market to motivate harvesting. Therefore, economic research on Red alder's product market to detect problems or factors for promoting Red alder use facilitates to develop the potential of Red alder.

Chapter 5. CONCLUSION

This study estimates carbon sequestration (CS) and global warming mitigation potential (GWMP) of Red alder and Douglas-fir in the long-term (100 years) and short-term (25 years), changing the condition of the plantation to understand the potential of Red alder as NCS. Regarding long-term, plantations of high-density with no treatment gain higher CS and GWMP than the other two different types of plantations in Red alder. Site index:65 accounts for the greatest proportions of Red alder landscape in WESTERN WA, 35%. The highest distribution of site index combination is the set of site index:65 for Red alder and site index: 145 for Douglas-fir. The second combination is a pair of site index:75 for Red alder and site index:145 for Douglas-fir. CS100 of Red alder (site index:65, high-density and no treatment condition) is 149.9 tCO2/acre/year at 30 years of harvesting age, 157.9 tCO_2/acre/year at 34 years of harvesting age. GWMP100 are 131.6 tCO_2eq/acre at 30 years of harvesting age and 147.2 tCO_2eq/acre at 40 years of harvesting age. CS100 of Red alder (high-density, no treatment) peaks at 34 years of harvesting age, while GWMP100 is maximum at 40 years. Those metrics stay almost steady after the age of 33 years. Corresponding Douglas-fir in site index:145 indicates 203.1 tCO_2/acre/year at 45 years of harvesting age, 240.5 tCO_2/acre/year at 55 years of harvesting age for CS100. GWMP100 are 187.7 tCO_2eq/acre at 45 years of harvesting age, 223.4 tCO2eq/acre at 54. CS100 peaks at the most prolonged harvesting age, while the apex of the GWMP100 is at 54 years. Comparing Red alder and Douglas-fir results in that Red alder is advantageous in both CS100 and GWMP100 in shorter harvesting ages such as less than 35 years. If landowners emphasize short-term harvesting roatation for reasons such as producing more logs, Red alder is preferable to yield more GWMP than Douglas-fir.

The total proportion of area in site index combination where Red alder exceeds Douglas-fir in GWMP100 is 18.7%. Douglas-fir has a higher chance of producing more GWMP100 contributing to mitigating global warming, than Red alder. Considering CS25 and GWMP25, this study estimates two cases for them, starting the timeframe from plantation of both species and starting the timeframe from manufacturing wood products of Douglas-fir. Both cases display Red alder's higher possibility of outpacing Douglas-fir in CS25. GWMP25 with the timespan from planting results in the same. Consequently, Red alder excels in more than 80% of the landscape in WESTERN WA than Douglas-fir. Red alder is the favorable option for forest management in terms of CS25 and GWMP25, in contrast to the estimation for the long term.

This study detects two ways to improve Red alder's potential to mitigate Global warming. First, finding an opportunity to utilize forest residue, especially for branches, instead of discarding as forest residue is one idea. Red alder holds a higher ratio of branches of the total above ground biomass than Douglas-fir, and the branches is the third largest contribution to GWMP100. However, branches are abandoned after harvesting, and it releases its carbon in short period through the decay of forest residue or burned slash piles. Hence, actualizing the use of forest residue for manufacturing wood products with a long functional lifetime potentially boosts the GWMP. Secondly, switching manufacturing wood products from paper to other wood products which can hold carbon for a prolonged period. Manufacturing paper and recycling paper produce more negative GWMP100 than positive GWMP100, which enhances global warming. Hence, replacing the factor generating influence to proceed global warming leads to improve Red alder's GWMP.

To comprehend the preferable forest management way without losing economic profitability, this study calculates the net present value (NPV). The highest NPVs with 5% discount rate are -

$263/acre for Red alder (site index: 65), $109/acre for Red alder (site index:75), and $647/acre for Douglas-fir (site index:145) in the 5% discount rate. Regarding NPVs with 7% discount rate, . Red alder tends to have the peaks of NPVs in younger harvesting age around 25 years, while Douglas-fir inclines to reach later than 40 years. The sum of the percentage of Red alder with site index where plantations induce positive NPVs is 48.28%.

On the contrary, the NPVs with 7% discount rates result in Red alder gains 13.02% to have positive NPVs in WESTERN WA, which is a greater possibility than Douglas-fir. Following the results of NPVs, the optimal harvesting ages, which take the balance of NPV with the 5% rate and GWMP, are 25 years for Red alder (site index:75) and 50 years for Douglas-fir (site index: 145). Those ages are earlier by five years for Red alder, and later by five years for Douglas-fir than the typical ages which this study consider. Consequently, 25 years of harvesting age enable Red alder to not only balance both economic profitability and contribution to mitigating global warming, but also outpace Dougals-fir with the same harvesting age in GWMP100.

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APPENDIX A

Table A- 1. Carbon sequestration for Red alder with 100-year time horizon

(Unit: kg CO_2 / acre /year)

Density	Treatment	Harvesting age	Site index					
			35	45	55	65	75	85
High	No treatment	20	13413.13	37211.71	73436.33	116633.8	170968.1	241181.4
High	No treatment	21	14310.44	39237.51	76083.79	120865.2	174724.1	243488.1
High	No treatment	22	15923.37	42781.56	79714.71	125101.9	178803.3	245146
High	No treatment	23	18086.49	45498.95	84149.51	130594.1	184139.2	249603.2
High	No treatment	24	20124.95	48486.98	88030.88	136549.2	190074.8	255339.4
High	No treatment	25	21956.96	50189.61	92012.96	140600.7	193768.9	258913.3
High	No treatment	26	22952.2	51884.02	93575.78	142261.7	193351.2	259046.7
High	No treatment	27	23848.14	53395.69	94935.26	143613.2	194734.3	258261.1
High	No treatment	28	25288.46	55439.02	97163.72	145204.1	195822	258463.1
High	No treatment	29	26752.79	56584.93	99653.84	147449.4	196922.5	259877.7
High	No treatment	30	28471.37	59142.37	102198.5	149880.2	198827.7	263152
High	No treatment	31	30177.89	61806.18	105378.4	152572.5	201796.5	266950.6
High	No treatment	32	31590.95	63256	108231.6	155501.5	204461.7	269920.5
High	No treatment	33	33403.22	65710.16	110556.4	157443	206912.3	273287.4
High	No treatment	34	34142.76	66000.93	111166.8	157878.9	207641.6	273259
High	No treatment	35	34377.19	66070.72	111431.4	157470	207598.8	272316.3
High	No treatment	36	35083.13	66984.7	111838	156969.4	207083.4	272242.8
High	No treatment	37	35994.27	67512.98	112293.2	156746.1	207647.8	271581
High	No treatment	38	36553.81	68295.72	112404	156685.4	207420.6	271983
High	No treatment	39	36914.01	69278.68	112672.1	156876.8	207926.9	271421
High	No treatment	40	37534.7	69789.55	113266.1	157537.7	208377.7	271062.5
High	Thinning	20	10092.03	31482.75	55252.71	83334.45	122614.3	173001.2
High	Thinning	21	11234.25	33914.1	57016.46	85919.02	126585.8	176073.4
High	Thinning	22	12913.62	35087.11	59471.67	89590.13	131278.9	180294.1
High	Thinning	23	14761.5	36697.29	62231.82	94718.41	136593.6	185906.9
High	Thinning	24	16770.7	38340.65	65095.89	99103.4	142332.2	191643.6
High	Thinning	25	17815.96	39895	67557.12	102635.2	146362.2	197790.9
High	Thinning	26	18212.99	40896.4	68669.94	104066	147779.1	199520.8
High	Thinning	27	19647.59	41669.82	70315.98	105957.1	149518.2	202225.8
High	Thinning	28	20675.31	42754.26	72241.28	108047.1	151082.3	205660.7
High	Thinning	29	21419.45	44009.54	74414.17	110519.6	153964.8	209450.4
High	Thinning	30	22651.52	45434.01	77007.92	113747.5	157030.4	214409.3
High	Thinning	31	23458.39	46940.44	79849.38	116732.5	161146.4	219771.2
High	Thinning	32	24755.89	48648.91	82248.51	119706.9	165402.4	225126
High	Thinning	33	25540.56	50254.88	84567.05	122085.6	168703.3	228849.6
High	Thinning	34	25881.24	50374.78	85262.64	122848.9	170055.8	229809
High	Thinning	35	26100.26	50585.09	85847.33	122812.1	170254.3	230422.3
High	Thinning	36	26626	51444.88	86397.76	123231.6	171275.3	231617.7
High	Thinning	37	26811.73	51961.56	87011.66	124008.1	172025	232219.5
High	Thinning	38	27319.97	52648.97	87772.91	124997.3	173701.4	233051.7
High	Thinning	39	27819.89	53632.45	88787.86	125945.5	174950.1	234328.4
High	Thinning	40	28296.57	54201.64	90080.09	127410.2	176429	236096.7
Low	No treatment	20	8147.199	27341.01	44857.16	69212.83	109693.3	135929
Low	No treatment	21	9796.691	29703.01	46255.31	71171.27	113058.8	138533.7
Low	No treatment	22	11373.06	31438.18	48787.28	74197.64	117099.1	143444.1
Low	No treatment	23	12781.45	32955.73	51129.02	78251.76	121432.3	148458.5
Low	No treatment	24	14251.41	34440.53	53880	82704.57	126478.1	153468.4
Low	No treatment	25	15312.18	35828.77	56196.33	86360.22	130462.4	158438.4
Low	No treatment	26	15869.51	36375.8	57376.11	88003.56	131814.5	160179.3
Low	No treatment	27	16444.16	37223.68	58415.85	89843.46	133360.2	162371.2
Low	No treatment	28	17129.78	37825.93	60050.18	91835.43	135267.7	165289.3
Low	No treatment	29	18159.79	39403.69	61732.31	94134.23	138336.7	168264.4
Low	No treatment	30	19343.58	40815.03	64108.83	96760.3	141390.7	172421.4
Low	No treatment	31	20356.81	42575.55	66652.15	99701.08	144950.1	176836.1
Low	No treatment	32	21560.53	44473.02	69152.28	102729.3	148611.9	181192.6
Low	No treatment	33	22432.19	45659.43	71344.55	105344.3	151875.4	184988.7
Low	No treatment	34	22732.37	46268.17	72167.37	106159.9	153170.8	185736.1
Low	No treatment	35	22967.5	46680.15	72593.18	106664.6	153287.2	187001
Low	No treatment	36	23418.79	46929.74	73193.65	107463.9	154221.7	187446.5
Low	No treatment	37	23720.55	47431.33	74004.92	108204.5	154788.3	188767.6
Low	No treatment	38	24091.36	48505.48	74961.65	109100.5	155927.6	189852.8
Low	No treatment	39	24576.71	49167.81	75796.4	110062.3	157058.6	190973.1
Low	No treatment	40	25107.51	49979.63	76851.93	111476.8	158567.6	192542.2

Note: The Yellow cells are the highest value in the corresponding site indexon

Table A- 2. Global Warming Mitigation Potential for Red alder with 100-year time horizon (Unit: kg CO_2eq / acre)

Density	Treatment	Harvesting age	Site index					
			35	45	55	65	75	85
High	No treatment	20	18269.9	40338.3	69960.33	102973.8	141391.4	190214.1
High	No treatment	21	19036.3	41519.75	71314.39	104624.8	142871	191037.8
High	No treatment	22	20496.14	43717.83	73862.87	107594.3	145838.6	193387.8
High	No treatment	23	22505.82	46412.5	77776.74	112296.7	151071.2	198782.6
High	No treatment	24	24613.7	49553.29	82370.26	118399.9	158331.1	207176.8
High	No treatment	25	26443.71	52114.16	86570.54	123597.7	164595.3	212511.4
High	No treatment	26	26930.16	52796.45	87104.42	124002.6	164399	212678.7
High	No treatment	27	27624.81	53655.19	87947.63	124756.8	165131.9	213275.3
High	No treatment	28	28787.12	54975.74	89463.57	126149.9	166594	214780.3
High	No treatment	29	30142.18	56520.47	91684.27	128437.1	168867.5	217633.4
High	No treatment	30	31766.16	58765.13	94510.57	131605	172477.3	221995.6
High	No treatment	31	33548.85	61476.26	98035.39	135668.2	176919.2	228104.6
High	No treatment	32	35316.15	64010.46	101827.1	140407.7	182891.6	235205.3
High	No treatment	33	36972.18	66572.84	105220.6	144602.4	188373.3	242063.8
High	No treatment	34	37507.18	67230.76	106115	145670.5	189228.3	243776
High	No treatment	35	37652.01	67265.46	106122.1	145480.4	189272	243478.9
High	No treatment	36	37972.11	67570.54	106254.9	145373	189272.2	243515.8
High	No treatment	37	38360.99	67912.69	106506.5	145474.2	189699.5	243590.5
High	No treatment	38	38779.88	68410.59	106829.2	145784.4	190031.1	244117.1
High	No treatment	39	39297.12	69031.64	107350.1	146359.1	190748.6	244674.3
High	No treatment	40	39936.57	69748.1	108141.4	147252.2	191686	245550
High	Thinning	20	12386.41	29043.11	48321.39	70521.01	100606.6	136694.6
High	Thinning	21	13091.76	30167.58	49602.6	72165.52	102823.4	138879.1
High	Thinning	22	14248.3	31596.32	51926.09	75321.85	106821.6	143355
High	Thinning	23	15644.68	33550.45	55125.19	79987.46	112341.9	150302.4
High	Thinning	24	17234.63	35841.24	58809.3	85077.59	118993.4	158811.5
High	Thinning	25	18424.76	37928.78	62145.14	89625.06	124915.9	166735
High	Thinning	26	18681.33	38458.6	62831.55	90355.51	125642.7	167814.2
High	Thinning	27	19473.8	39227.24	64030.61	91753.4	127324.2	170095.5
High	Thinning	28	20373.69	40409.22	65828.56	93853.55	129738.4	173525.8
High	Thinning	29	21347.72	41978.61	68206.32	96729.54	133393.5	178246.5
High	Thinning	30	22625.41	43879.63	71140.17	100439.8	138042.8	184373.3
High	Thinning	31	23869.79	46031.62	74455.23	104537.4	143614.5	191431.5
High	Thinning	32	25265.54	48360.23	77844.82	108926.8	149560.6	199109.9
High	Thinning	33	26446.98	50453.54	80934	112907.9	155007.7	205832.6
High	Thinning	34	26849.17	51034.07	81893.92	114123.4	156705.6	207775.7
High	Thinning	35	27002.04	51281.08	82149.01	114283.4	156980	208071.8
High	Thinning	36	27311.53	51753.43	82563.65	114773.5	157605.1	208695.9
High	Thinning	37	27639.89	52282.27	83162.27	115519.8	158443.2	209460
High	Thinning	38	28108.51	52954.69	83989.75	116549.9	159757.3	210553.6
High	Thinning	39	28671.04	53803.47	85049.81	117814	161205.1	212094.9
High	Thinning	40	29339.02	54718.06	86412.24	119440.1	163040.2	214141.9
Low	No treatment	20	10442.67	26372.42	40610.11	60551.85	91819.27	111599.3
Low	No treatment	21	11319.26	27515.15	41678.14	62017.09	93830.08	113529.2
Low	No treatment	22	12440.85	29055.85	43868.45	64856.26	97235.24	117729.9
Low	No treatment	23	13715.31	31062.32	46731.58	69061.92	102234	123704.1
Low	No treatment	24	15115.08	33283.02	50193.07	74070.41	108494.6	130997.1
Low	No treatment	25	16269.12	35260.7	53240.95	78398.84	114087.2	137764.5
Low	No treatment	26	16582.37	35611.26	53942.33	79252.59	114854.5	138854.5
Low	No treatment	27	17103.41	36387.15	54971.46	80627.63	116278.5	140700.4
Low	No treatment	28	17861.17	37439.74	56592.66	82595.59	118566.4	143640.7
Low	No treatment	29	18913.79	39107.86	58688.62	85264.55	122005.6	147544.9
Low	No treatment	30	20164.68	41030.1	61374.47	88653.08	126318.2	152712.6
Low	No treatment	31	21473.02	43242.85	64481.99	92672.78	131432.8	158884.9
Low	No treatment	32	22841.65	45575.37	67681.62	96938.3	137034.4	165488.3
Low	No treatment	33	23999.28	47517.88	70541.34	100773.1	142067.4	171454.7
Low	No treatment	34	24383.16	48221.29	71478.99	101962.5	143686.1	173128.1
Low	No treatment	35	24575.31	48476.16	71752.54	102247	143924	173558.9
Low	No treatment	36	24857.2	48819.2	72194.6	102810.8	144539.4	174064.4
Low	No treatment	37	25194.58	49312.87	72818.37	103545.6	145242.9	174995.9
Low	No treatment	38	25644.63	50076.67	73632.35	104493.9	146300.3	176695.4
Low	No treatment	39	26214.03	50873.57	74602.3	105690.2	147622.3	178567.8
Low	No treatment	40	26889	51839.4	75784.59	107169.7	149353.5	180440

Note: The Yellow cells are the highest value in the corresponding site index

Table A- 3. Carbon sequestration for Douglas-fir with 100-year time horizon

(Unit: kg CO_2 / acre / year)

Harvesting age	site index								
	85	95	105	115	125	135	145	155	165
20	15250.36	17780.26	23817.08	26959.04	34450.2	37437.45	40824.66	44548.79	50980.05
21	16118.87	18805.32	25036.11	28338.58	35989.75	39091.19	42759.12	48379.2	57505.54
22	17698.78	20659.66	27244.59	30837.09	38803.71	42451.28	47787.97	55794.83	65486.43
23	19793.33	23123.47	30187.81	34165.7	43093.44	48120.88	55433.36	64088.3	75523.73
24	22063.51	25782.81	33418.36	37821.67	48907.17	55368.57	63487.35	73154.54	87946.9
25	24094.93	28159.93	36309.21	41094.49	54752.8	62062.65	71272.11	83659.14	97681.32
26	24785.24	28958.01	37220.99	43146.97	58451.12	66227.66	77521.08	89530.71	104785.7
27	26004.85	30376.25	38847.85	47116.74	63107.93	72347.73	83618.05	96845.28	111336.5
28	27703.37	32353.89	42221.49	51328	69303.33	79044.86	91305.96	104108.7	119274
29	29815.21	34810.07	46737.59	56581.37	75335.63	86342.23	98923.23	112353.7	129055.3
30	32244.71	37640.13	51194.1	62124.05	82458.99	93809.22	106273	120807.7	138889.1
31	34851.89	40681.51	56085.92	68283.37	89893.99	101249.6	115122	129989.4	150725.2
32	37429.56	44611.56	61379.11	74965.84	96604.4	108449.7	122575.4	139884.4	161450.9
33	39749.87	49067.07	66126.1	80901.44	102767.2	115397	131088.8	149384.5	171170.3
34	40660.33	50692.64	70018.7	84095.89	106353.3	119774	136062.9	154954.5	177521.3
35	42063.65	52526.46	72099.43	87225.65	110158.2	123521.3	141187.7	160124.8	183746.7
36	43375.87	54677.75	75289.54	89893.65	113650.2	128133.7	146478.7	166323.7	189724.6
37	45805.52	57191.75	78195.38	93468.39	117729.6	133341.2	151787.2	172275.5	195558.1
38	47927.15	60051.17	81668	97037.96	122245	138415.9	157611.7	178941.1	201859.8
39	50015.63	63488.95	84759.87	102303.6	126846.2	144020.3	163734.3	184983	208326.5
40	52776.48	66984.76	87913.28	105528.5	132037.3	149876.8	170167.9	191629.3	214744.6
41	55579.68	70208.34	92567.7	110948.9	137962.8	156085.8	176674.9	198145.2	220836.1
42	58757.59	74126.52	96482.36	115102.4	143457.2	162195.4	183659.6	204599.7	227250.9
43	62354.98	78185.53	100576.4	119852.7	149708.7	169020.5	190638.4	211053	233896.9
44	65682.53	81405.43	105278.4	125054.7	155573.6	175342	196755.8	217608.3	241723.3
45	69096.67	85397.57	109996	130641.1	161539.7	181762.5	203121.3	224147.2	249389.3
46	72138.5	89033.04	114298.9	136407.2	168192.7	188075.1	209346.6	230776.5	257262.9
47	75891.29	92998.24	117944.7	142041.9	173858.9	194077.2	215111.8	237311.1	264324.8
48	78410.35	96327.53	122655.1	146744.7	179070.9	199624	221111.4	244143.5	270578.7
49	81549.8	99554.22	126126	151766.5	183838.6	204486.8	226258.7	250815.9	276946.9
50	83754.91	103081	129905.4	155495.5	188410.3	209104.7	231336	255880.4	281938.5
51	84349.02	103426.9	131491.1	156935	189749.1	210057	233216.9	257520.1	283962.2
52	85374.94	104247.7	132632	158617.9	191120.2	211825	235115.1	258779.4	286170
53	86102.86	105464.6	134471.9	159858.6	192576.9	213300.7	237074	260655.5	287475.2
54	86745.32	107141.5	135300.2	161658	193894	215233.7	238945.9	262729.6	289155.7
55	88013.09	107792.6	137256.1	163328	195619.7	217165.6	240472	264799.1	291918.1

Note: The Yellow cells are the highest value in the corresponding site index

Table A- 4. Global Warming Mitigation Potential for Douglas-fir with 100-year time horizon (Unit: kg CO_2eq / acre)

	site index								
Harvesting age	85	95	105	115	125	135	145	155	165
20	23167.09	27023.34	35992.65	40756.46	51773.77	56217.52	61306.97	66867.75	73867.1
21	24303.36	28358.65	37568	42539.84	53738.44	58323.1	63655.83	69936.83	77668.85
22	26464.01	30898.97	40521.45	45914	57484.77	62439.3	68543.42	75676.48	83899.45
23	29423.67	34390.95	44625.65	50561.04	62837.72	68495.19	75441.42	83139.59	92284.11
24	32705.55	38239.53	49242.95	55792.74	69274.55	75643.72	83237.78	91773.51	102005
25	35617.38	41644.38	53353.16	60443.78	75186.86	82176.9	90454.59	99955.3	110662
26	36461.47	42611.36	54444.26	61983.41	77181.31	84285.76	93058.92	102470.2	113242.1
27	37998.59	44395.87	56452.86	64806.51	80236.39	87929.24	96834.23	106512.9	117111.6
28	40178.49	46926.4	59660.43	68415.47	84576.34	92551.31	101914.4	111688.1	122687.4
29	42935.25	50131.14	63740.46	73058.33	89628.25	98031.1	107792.5	118106.3	129754.1
30	46167.34	53875.77	68279.51	78308.93	95466.29	104431.4	114566.7	125504.3	137789.4
31	49688.9	57980.91	73318	84006.96	102015.8	111366.2	122375	133594.5	146981.1
32	53163.51	62306.86	78486.71	89936.02	108494.5	118537.1	130211.4	142239.1	156374.5
33	56293.96	66408.98	83166.77	95323.62	114607	125279.1	137569	150476.5	165091.2
34	57440.85	67910.21	85015.79	97439.33	116985.7	127926.5	140466.6	153788.9	168440.1
35	58260.44	68897.04	86053.34	98597.82	118316.3	129189.8	142083.4	155417.3	169878.9
36	59297.82	70255.17	87527.48	100152.3	120013.6	131160.4	144250.3	157561.3	172200.5
37	60835.01	71783.47	89263.63	102067.2	122243	133570.9	147007.4	160212.4	174969.6
38	62498.62	73705.8	91383.15	104544.2	124928.1	136686.8	150259.2	163673.1	178170.1
39	64392.22	75951.59	93905.45	107522.9	128216.8	140206.6	154077	167749.7	181771.3
40	66720.53	78620.46	96647.21	110680	132082	144351.8	158549.4	172113.5	186243.4
41	69159.51	81483.31	100009.5	114596.3	136409.9	148857.5	163659.1	177332.2	191025.4
42	71913.03	84727.92	103551.6	118625.8	141137.4	154069.2	169253.8	182509.1	197157.1
43	74885.76	88247.12	107409	123271.1	146313.4	159716.2	174973.5	188543	203133
44	78030.75	91900.41	111655.8	128275.9	151827.2	165806.8	180740.1	195108.5	210179.7
45	81441.28	95793.14	116233.7	133582.9	157723.5	171980	187742.3	202510.1	217610.5
46	84797.75	99760.31	120887.2	139114.7	163949.7	178735.2	194487.7	209326.1	225658
47	88214.15	103754.3	125647	144669.5	170060.2	185122.9	202038.2	217129.9	234009.7
48	91472.06	107608.4	130365.2	150097.4	176506.3	192185.4	209342.7	225047.8	242914.4
49	94609.92	111300.2	134987.1	155500.3	182236.9	198436.8	216158.3	232937.2	251018.9
50	97355.4	114733.1	139192.3	160469.6	188114.4	204890.4	223030.8	240275	259197.9
51	97522.78	114856	139439.4	160636.1	188042.6	204192.7	222803.2	240303.4	258792.4
52	97700.49	115110.2	139652.4	161004.1	188048.8	204429.2	222521.8	239804.4	258971.7
53	97980.91	115460.7	140021.1	161215.9	188517.1	204605.9	222845.2	239868.6	259249.7
54	98298.51	115776.4	140453.4	161282.1	188370.7	204916.4	223386	240103	259128.1
55	98670.25	116211.8	141013.9	162020.3	189049.4	205171	223141.7	240822.3	259384.9

Note: The Yellow cells are the highest value in the corresponding site index