



# Economic gain of genetically-selected coastal Douglas-fir: Timber, log and carbon value at varying planting densities

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## ABSTRACT

Substantial investments in tree breeding for coastal Douglas-fir in British Columbia are projected to lead to significant volume gain at rotation age. Recent research shows growth gains are accumulating as expected, but it is less clear to what degree and when these volume gains translate into economic gains. We use discounted cash flow analysis techniques to quantify economic gains and determine optimal rotation ages expected from planting three levels of genetic gain in tree volume (a 0 % control, +10 % and +18 %) at four initial densities (625, 1189, 1890 and 3906 stems/ha). Valuations were estimated for a variety of economic conditions for timber volume and log grades, with and without carbon pricing. These analyses rely on a growth and yield model simulating data from a 21-year coastal Douglas-fir realized gain trial, installed on five sites differing in productivity. Simulations show that planting selectively-bred coastal Douglas-fir trees reliably led to significant economic gains relative to unselected control stands, across initial planting densities, sites and varied economic scenarios. Highest financial returns are projected for genetically-selected seedlings at the most productive sites. Lower initial planting densities were associated with higher economic gains but also reduced important wood quality metrics that were not captured by the financial analyses, suggesting that operational planting densities (1189–1890 stems/ha) could offer a suitable compromise. Incorporating carbon prices led to larger economic returns and longer rotations. Altogether, these simulations suggest that a reliably higher return on investment can be achieved by deploying selectively-bred planting stock.

## 1. Introduction

Forestry is the economic backbone of many communities in British Columbia (BC), Canada. In 2020, for example, the BC forest sector contributed more than \$5.5 billion to the provincial GDP, generated \$1.1 billion in public revenue and sustained over 42,000 jobs (Bautista, 2020). The province's diverse forests are also ecologically and culturally important. To sustain these values, it is crucial to establish productive and resilient forests after harvesting. This is supported by substantial annual investments in reforestation in BC: Every year, 250–300 million seedlings are planted at about \$1 per tree.<sup>1</sup> To further promote long-term forest health and productivity, provincial reforestation policies require the use of genetically-selected seed, if available, derived from

tree breeding programs (Nicholls, 2022). Tree breeding programs, also known as genetic selection or tree improvement programs, evaluate genetic variation naturally occurring in tree populations to make selections for desirable traits such as growth and disease resistance. In BC, many tree breeding programs have been continuously operating for several decades. These efforts have resulted in large genetic gains, which are the overall increase for desirable traits due to artificial selection relative to natural populations (also referred to as “wild-stand”, “woodsrun” or “class B” seed) (Xie and Yanchuk, 2003).

Tree breeding programs involve iterative – and costly – processes of selection, breeding and field testing. They are integrated with seed production by supplying seed orchards with genetically-selected trees. Seed orchards, in turn, provide a reliable supply of seed with a known

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level of genetic gain for use in reforestation programs (Stoehr et al., 2004). These seedlots are referred to as “improved” or “class A” seed in BC. Although the costs of supporting these activities translate to a higher price for genetically-selected seed compared to wild-stand seed, good return on investment is expected since tree breeding programs involve rigorous testing to provide assurance on genetic gains, to maintain adaptation to local environments, and to carefully control genetic diversity (Howe et al., 2006; Stoehr et al., 2004).

Due to the costs involved, tree breeding programs are often established only for the most ecologically important or economically valuable timber species (McKenney et al., 1992; McKenney et al., 1989; Stoehr et al., 2004). The economic value of establishing tree breeding programs has long been recognized, with the literature indicating such programs provide a good return on investment (e.g., Carlisle and Teich, 1971; Kimberley et al., 2015; Schreiber and Thomas, 2017). From a land manager’s perspective, many studies have also suggested that deploying genetically-selected planting stock is a better investment for reforestation (Ahtikoski et al., 2018; Ahtikoski et al., 2012; Ahtikoski and Pulkkinen, 2003; Chamberland et al., 2020; Jansson et al., 2017; McKeand et al., 2006; Petrinovic et al., 2009; Simonsen et al., 2010). In BC, the Tree Improvement Investment Priorities (TIIP) model was developed to determine value of provincial tree breeding programs based on factors such as genetic gain, area for seed deployment and timber value (Woods, 2002). Currently, the top-priority breeding program for the province under this model is coastal Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*).

Douglas-fir is a key foundation species for coastal ecosystems of western North America. It is also one of the most valuable timber species in Canada and is prized for its wood quality (Aubry et al., 1998; Hermann and Lavender, 1999; Lowell et al., 2014). Early recognition of these values led to BC’s first tree breeding program being developed for coastal Douglas-fir, beginning in the 1950’s (Heaman, 1967; Orr-Ewing, 1969). Recurrent selection in this program has primarily aimed to increase timber volume at rotation age (Heaman, 1982; Heaman, 1967). Maintaining wood quality in the breeding program has been an important secondary objective (Heaman, 1967; Stoehr et al., 2004; Ukrainetz et al., 2008), especially because Douglas-fir is expected to continue occupying high-quality lumber markets as less valuable wood products from other species become more available (Aubry et al., 1998). Relative to wild-stand seed, BC’s coastal Douglas-fir seed orchards are now supplying the province with planting material having expected genetic gains of 15–22 % more volume at a rotation age of 60 years (SPAR, 2024). These gains in volume can be fully realized at rotation or may be used to justify shorter rotations (Howe et al., 2006; Serrano-León et al., 2021). In the US Pacific Northwest for example, operational rotation ages are reported to commonly be 45–55 years (Joo et al., 2020). These large genetic gains in volume also accelerate early growth in the seedling stage, leading to faster free-growing status and green-up that provide operational flexibility through adjacency gains (Stoehr et al., 2004).

Planting trees selected for desirable traits like volume and wood quality is expected to yield higher economic returns, promote carbon sequestration, and provide socio-economic benefits that positively impact people’s lives in the long-term. To justify higher costs, it is important to verify expected benefits from deploying genetically-selected seedlots for one of the province’s most valuable timber species. This includes verifying genetic gains for volume as well as analyzing net financial returns after considering higher establishment costs, timber value, lumber grades and impacts on wood quality. Earlier research using coastal Douglas-fir realized gain trials suggests that genetic gains in volume are generally materializing across the Canadian and US Pacific Northwest (Isaac-Renton et al., 2020; Joo et al., 2020; Stoehr et al., 2010; Ye et al., 2010). In British Columbia, analyses have also suggested that deploying genetically-selected seed at higher operational planting densities could maximize volume gain per hectare while helping maintain wood quality (Isaac-Renton et al., 2020). Remaining

unclear is how the silvicultural decisions of operational planting densities interact with genetic gain in terms of financial return on investment. While better log grades resulting from planting genetically-selected seed more densely could yield higher premiums, genetically-selected seed are more expensive, and higher initial planting densities increase planting costs. Carrying this cost of planting forward to rotation may reduce financial returns.

To compare financial returns of different silvicultural decisions, costs and benefits over silvicultural rotations are incorporated into discounted cash flow analyses. These analyses estimate the present value of forecasted cash flows, or net present value (NPV), using a discount rate, or interest expressed as a percentage. Because outputs are reported in a common dollar year, net financial returns of different investments can be compared at a particular discount rate. A positive NPV indicates that an investment is forecasted to be profitable while negative NPV suggests the costs of an investment will exceed the financial benefits. To facilitate comparisons of different investment options, economists refer to incremental gains or costs, which are the per-unit financial benefits or costs. For example, if planting genetically-selected seed leads to positive incremental benefits, it would imply that it is more profitable than planting non-selected seed. This represents the return on investment from planting genetically-selected seed. In forest economics, the concept of NPV and incremental benefits or losses is often extended to Site Expectation Value (SEV). The SEV represents the present value of cashflows from a silvicultural decision over a theoretical infinite series of rotations of the same length (Faustmann, 1995; Faustmann, 1849). The SEV solves the problems of comparing forest investments that would yield rotations of varying lengths. The Faustmann model accounts for revenue from timber harvest as well as the time-cost of potentially delaying harvests (Foley et al., 2009).

Different approaches to estimating financial returns can also have substantial impact on return on investment and rotation ages. For example, in addition to estimating financial returns for timber using the Faustmann model, which is a more traditional approach, accounting for potential premiums from better log grades produced under certain silvicultural scenarios may alter decisions. Generally, lower stand densities are expected to produce higher individual-tree volumes (but lower volume per unit area) that yield greater merchantable volume per log. At the same time, lower stand densities are also expected to produce trees with characteristics that reduce wood quality and value, e.g., thicker branches and larger live crowns (Lowell et al., 2014). Including non-timber values can also affect economic returns and financially optimal rotation ages in Douglas-fir forests (Calish et al., 1978; van Kooten et al., 2019; van Kooten et al., 1995). As atmospheric carbon is becoming an increasing concern, for instance, emerging carbon markets in forestry offer alternative economic models involving carbon pricing to incentivize climate change mitigation (Foley et al., 2009; Plantinga and Birdsey, 1994; van Kooten et al., 1995). Including carbon prices along with timber values using a modified Faustmann approach developed by van Kooten et al. (1995) may alter financially-oriented decisions on seedlot selection. Higher economic returns from incorporating carbon value in forestry financial analyses has also been reported in the literature (e.g., Dwivedi et al., 2009).

Estimating the impacts of these economic considerations at the intersection of tree breeding and silviculture is crucial to informing real-world decisions where margins are increasingly tight, and stochastic variability due to climate change is an increasingly real threat to productivity. It is therefore important to study interactions between genetic gain with stand density and site as they could lead to different economic returns (Carlisle and Teich, 1971; Dash et al., 2019). In particular, many authors have reported that benefits can be maximized by deploying the best-quality seedlots on the better quality sites (Chamberland et al., 2020; Chang et al., 2019; Dash et al., 2019; Kimberley et al., 2015; Lee et al., 2017; McKeand et al., 2006; McKenney et al., 1992; McKenney et al., 1989; Petrinovic et al., 2009).

Here, we use discounted cash flow analyses to estimate the economic

return associated with three genetic gain levels of coastal Douglas-fir established under four initial planting densities. Specifically, we aim to answer: 1) How can deploying genetically-selected seed sources be combined with initial planting density to optimize volume and value? 2) Are higher initial planting densities economically worthwhile, with better wood quality compensating for higher site establishment costs? 3) Does incorporating carbon pricing alter the approach to deploying and managing genetically-selected planting stock? Our study uses data from a coastal Douglas-fir realized gain trial to calibrate a growth and yield model until age 21 for three levels of genetic gain established under a variety of planting conditions. This model is used to project volume growth and log grades over time, which forms the basis of discounted cash flow analyses for a range of hypothetical economic conditions and carbon pricing. The aim of this work is to guide seed deployment to maximize value from timber, logs and carbon pools. With approximately 15 million coastal Douglas-fir seedlings planted annually, and the majority being from genetically-selected seed sources derived from the tree breeding program, optimizing reforestation practices could lead to widespread and long-term benefits.

## 2. Methods

### 2.1. Experimental design of the coastal Douglas-fir realized gain trial

The coastal Douglas-fir realized gain trial comprises five sites in low-elevation areas of southern BC characterized by wet, mild, oceanic climates. These sites were chosen to represent a range of potential productivities, described further below. Each site contains two replications testing factorial combinations of three classes of genetically-selected stock and four initial planting densities. These treatment combinations were installed as block plots of 144 trees (planted in a 12 × 12 square grid) in 1996 with 1-year old container-grown seedlings. Buffer trees were planted between plots. To further reduce edge effects, tree size measurements were recorded on only the central 100 trees in the fall of 2015. As seeds were sown in spring of 1995 and resulting seedlings were planted in spring of 1996, height and diameter measured in autumn 2015 correspond to age 20 from planting and age 21 from seed.

The experimental design includes three classes or levels of predicted genetic gain for volume at a theoretical rotation age of 60 years, based on assessments of parent tree breeding values derived from offspring performance in highly-replicated progeny trials. Tree height and diameter measurements at age 12 (selection age) were used to estimate parental breeding values for gross tree volume following Omule et al. (1987), expressed as a percentage relative to the control (Stoehr et al., 2010). A juvenile-mature (age-age) correlation of 0.5 is used to predict tree volume at 60 years (Lambeth, 1980; Stoehr et al., 2010). While 60 years is used to represent a typical rotation age in coastal BC (Xie and Yanchuk, 2003), actual rotations for coastal Douglas-fir typically range from 40 to 80 years based on various factors. Because progeny are planted in single-tree plots without prior knowledge of performance, however, there is potential for inflation of estimates due to competitive effects (Magnussen, 1989). Therefore, realized gain trials are established in large blocks of trees with similar genetic gain levels to minimize competitive effects and retrospectively assess predictions over time (Stoehr et al., 2010).

The genetic gain levels in this realized gain trial were created through control crosses of parents with breeding values for volume at 60 years. As described by Stoehr et al. (2010), the top-cross level represents an average volume gain of 18 %, created through crosses among 10 parent trees with the highest breeding values at the time (17 to 26 %). The mid-gain level represents a mix of families with volume gains averaging 10 %. We note that the tree breeding program has advanced since the establishment of this trial, allowing for higher genetic gain levels, with current expected gains of 15–22 % from BC seed orchards for volume at age 60 (SPAR, 2024). A wild-stand or woodsrun level serves as a control, representing a mix of six local seedlots collected from natural

stands with 0 % genetic gain. All wild-stand seedlots were collected from the same seed planning zone, which at the time was based on geographic surrogates for climatic similarity and deployment suitability. The same planting stock was used on all sites as they were all located in the same seedlot deployment area. Thus, the wild-stand is not necessarily representative of a local source at any given site, but rather a mixture of 6 seedlots representing BC's productive coastal ecosystems. While there are differences in growth between these seedlots, their origin is not predictive of their performance, which is reasonably consistent across all sites and spacings.

With climate change, there may be concerns that local wild-stand seedlots could become less suitable as a control. It is well-recognized, for example, that as climates continue to change, local seedlots are expected to become increasingly maladapted (O'Neill et al., 2017; O'Neill et al., 2008). If the genetic gain levels have different adaptive portfolios, productivity associated with genetic selection could become confounded with climate adaptation. Currently, evidence for this is limited. Earlier analyses in coastal Douglas-fir found that adaptive differences from artificial selection would only materialize if transferred into environments much further than the maximum recommended transfer distance (O'Neill et al., 2014). As warming continues at the site, larger changes in relative productivity may therefore take longer to appear. As severe heat-drought events become increasingly more common, however, selected seedlots may have additional advantages due to a positive genetic correlation between height and drought resilience (Isaac-Renton, 2021). It does not seem that this threshold has been passed yet, though, since new growth ring data in this realized gain experiment found no differences in drought resilience among genetic gain levels (Damen et al., 2025). Altogether, it is reasonable for the comparative assessments here to assume that climate change has not yet altered gains in productivity due to differing impacts of maladaptation, and that the local wild-stand seedlots remain an effective control.

Predicted genetic gains in volume at age 60 can also be converted into per hectare volume due to the trial's spatially-explicit design that incorporates different initial planting densities. One-year old seedlings from these genetic gain levels were planted at four initial planting densities: 625, 1189, 1890, and 3906 stems per hectare (sph). The 1189 sph treatment approximates operational planting densities, bracketed by 625 and 1890 sph as very low and high operational comparisons. The 3906 sph treatment was included in the experimental design to provide data for growth and yield modeling. Initial planting densities for coastal Douglas-fir across the Pacific Northwest have varied over time (Talbert and Marshall, 2005), but in BC, have ranged from 600 to 1300 sph (Arnott, 1986). Anecdotally, 1200 sph is very common in BC but planting densities have also ranged up to 1400 sph. This is designed to achieve stocking densities between 500 and 900 sph during free-growing surveys which generally occur from eight to 11 years after planting. We consider the 1189 sph plots in our base analyses but explore the additional 625, 1890 and 3906 densities for some analyses of incremental SEVs.

### 2.2. Growth & yield modeling

Growth and yield projections were generated using BC's Tree and Stand Simulator model (TASS V2.07.76) for each stand in the trial. The TASS model is a spatially-explicit, individual-tree model that accounts for crown interactions and tree-to-tree variation. Individual tree growth functions within the simulator are developed from stem analysis data, with stand-level yields calibrated against re-measured permanent field plot data and adjusted for operational conditions. The model also includes modules for adding genetic gain to the projections. Stand development simulation in TASS is driven by individual tree height growth, with potential dominant height growth largely determined by site index, a standard measure of site productivity. For coastal Douglas-fir, the model calibration reflects the existing data across the species range in BC. To apply the model in this study, there are two possible

approaches: 1) Estimate site index at each site based on an average of dominant height increments between two plot measurements (e.g., age 12 and 21) (Bruce, 1981) and run the simulator with the genetic gain multipliers before predicting economic value, or 2) localizing TASS for these particular field plots by constructing custom site curves and mortality sequences and adjusting other functions using the plot data. Using growth & yield models calibrated with realized gain trial data (i. e., method 2) has been recommended for improving accuracy of productivity and profitability estimates (Serrano-León et al., 2021). We opted for a simplified variation of method 2 as it has the advantage of reflecting measurements from the experiment, whereas method 1 would produce a generic simulation exercise based only on the current TASS assumptions and predictions.

To incorporate the real-world observations into the simulations, we determined the SI required to predict the measured wild-seed stand-level volumes at age 21 for each site by planting density combination through iteration. This ‘calibrates’ the model for each site and density, and incorporates both the growth and mortality information from the field data. The resulting projections provide a baseline against which the performance of genetically-selected planting stock could be compared. In combination with these calibrated SI values, existing genetic gain modules in TASS were used to project growth of the 10 % and 18 % genetic gain trees beyond age 21. Although calibrating TASS simulations to observed yields improves confidence in mid- and later-term projections, confidence declines beyond the 21-year stand age observed data range as modeling tree growth necessarily incorporates uncertainty. We did not adjust the models further with mortality data. As our aim was to test the genetic worth assumptions and programming in the model, we accept the dynamics the model applies to mimic the age 21 yields and then project them forward.

We note that using this method yielded higher average estimates of site productivity compared to method 1. The estimated SI values for the five sites (in meters at breast height age 50) calculated from average dominant height increments (method 1)<sup>2</sup> versus our method are as follows: Spirit Lake 28.5 vs. 30.8; Lang Bay 35.4 vs. 34.1; Norrish Creek 37.3 vs. 45.2; Campbell River 39.6 vs. 42.1; and Robertson 42.8 vs. 44.8. As higher site productivity estimates would be expected to increase timber and log volumes, financial returns would also be higher than using the simulation-only approach. Thus, while we primarily present results from our method in the main manuscript, for rigour, we also assessed the impact of the SI estimates. Results of this re-analysis using method 1 are provided in the Appendix.

We used the growth curves to estimate timber, carbon, and log volumes and wood quality traits (juvenile wood proportion, branch thickness and stem taper ratio) for each stand in 5-year intervals from bare ground to age 120. Growth projections were simulated on one-hectare plots for each genetic gain class by initial planting density treatment combination at each site. Operational adjustment factors (OAFs), which reduce projected yields to account for incomplete site occupancy and other productivity-limiting factors (insects, disease, abiotic agents), were applied at the default levels of 0.85 and 0.95 (OAF1 and OAF2 respectively). These affect the projections differently and interact throughout the length of the projection. We modeled merchantable timber yields as well as carbon (metric tonnes/ha). We also used the bucking simulator module (SmartAxe) in TASS to estimate log volumes by grade for each treatment combination at each site. Bucking was optimized based on a vector of relative log prices derived from Coastal Log Market reports between 2010 and 2020. The SmartAxe module incorporates some aspects of wood quality in that the optimization routine is sensitive to the maximum and average branch proximal diameter at each stem node. Although the TASS model also accounts for crown recession (crown lift) at the individual-tree level, yielding estimates of juvenile wood proportion, this is not currently considered in the bucking

optimization.

### 2.3. Analysis of timber volume and value

To estimate the financial value from the timber produced in a stand, we used a discount-cash flow analysis model with a base initial planting density of 1189 sph for three levels of genetic gain (0 %, 10 % and 18 % expected volume gain at rotation age). To estimate timber pricing, base stumpage rates were derived by averaging the inflation-adjusted annual coastal Douglas-fir stumpage averages from 2010 to 2020, expressed in 2020 dollars per cubic metre. Stumpage was calculated using BC Timber Sales (BCTS) scaling data from 2010 to 2020 for the four forestry districts containing the five realized gain trials sites: Campbell River, Chilliwack, South Island, and Sunshine Coast. The BCTS data were accessed through the Harvest Billing System (<https://a100.gov.bc.ca/pub/hbs/>). For sensitivity analyses, alternative stumpage rates were calculated from the average rates of the bottom and top 25 % rate quantiles of years between 2010 and 2020.

Our methods follow a discounted cash flow model described in Bogdanski et al. (2018), modified to allow for comparison between genetic gain levels and to add density-dependent planting costs. We measured stand values as site expectation values (SEV). Site expectation value, sometimes simply called “site value”, but also referred to as bare land value or land expectation value, is the sum of discounted cash flows from an infinite series of rotations: Costs and benefits from stands are assumed to repeat over identical successive forest crops of a fixed rotation age selected to maximize SEV. Site expectation values of timber and corresponding optimal rotation ages for treatments were calculated using the following formulas (Faustmann, 1995; Faustmann, 1849):

$$\max_T SEV^i(T) = \frac{V_i(T) - s_0(1+r)^T - e_0(1+r)^T}{(1+r)^T - 1} \quad (1)$$

$$\max_T SEV^u(T) = \frac{V_u(T) - e_0(1+r)^T}{(1+r)^T - 1} \quad (2)$$

where  $T$  is rotation age,  $V_i(T)$  is the value of an improved stand at rotation age,  $V_u(T)$  is the value of an unimproved stand at rotation age,  $s_0$  is the incremental cost of improved seed at stand age 0,  $e_0$  is the planting establishment cost at stand age 0, and  $r$  is the discount rate or time value of money. In our timber analysis,  $V_i(T)$  and  $V_u(T)$  were calculated as the product of the standing timber price ( $p$ , \$/m<sup>3</sup>) and the merchantable wood volume ( $q$ , m<sup>3</sup>/ha) of the stand at rotation age. Standing timber refers to the living (uncut) trees in the area.

Incremental gains associated with planting improved seed were calculated as:

$$\text{Incremental SEV} = SEV^* - SEV^{u*} \quad (3)$$

where  $SEV^*$  is the site expectation value of an improved stand at the optimal rotation age calculated in eq. (1) and  $SEV^{u*}$  is the site expectation value of an unimproved stand at the optimal rotation age calculated in eq. (2). Positive incremental site expectation values would indicate positive return on investment from planting genetically-selected seedlings relative to unselected (wild-stand) seedlings. Any results we report as dollar values refer to Canadian dollars (CAD or Can \$). All analyses were conducted in the R-4.2.0 statistical programming environment (R Core Team, 2024).

### 2.4. Analysis of log grade volume and value

Since different genetic gain levels or initial planting densities could alter the proportion of log grades, which differ in value, we also calculated the incremental SEV of logs. We used the estimated log grade volumes from the SmartAxe module in TASS and stand log prices to calculate log values at rotation age. Log grades are assigned based on

<sup>2</sup> E. McWilliams, pers. comm. February 15, 2023

**Table 1**  
Parameters. All parameters as used in base analyses, for Monte Carlo sensitivity analyses of economic variables, and three hypothetical economic scenarios.

Parameter	Base Values	Economic Scenario		
		Monte Carlo Sensitivity Analyses	Good	Poor
p – Standing timber price (\$/m <sup>3</sup> )	40	10, 25, 40, 55, 70, 85	55	25
p <sub>H</sub> , p <sub>I</sub> , p <sub>J</sub> , p <sub>U</sub> , p <sub>X</sub> , p <sub>Y</sub> – Standing log prices per grade (\$/m <sup>3</sup> )	67, 42, 34, 20, 15, 12	–	92, 58, 46, 28, 20, 17	42, 26, 21, 13, 9, 8
e – Planting cost (\$/seedling without incremental seed cost)	0.92	0.42, 0.67, 0.92, 1.42	0.42	1.42
s – Incremental improved seed cost (\$/seedling)	0.08	0.06, 0.08, 0.1, 0.12, 0.14	0.06	0.1
r – Discount rate (%)	3	2, 3, 4, 5, 6	3	3
τ – Carbon price (\$/tonne CO <sub>2</sub> )	15	–	10, 25, 50	10, 25, 50
			Average	
			40	
			67, 42, 34, 20, 15, 12	
			0.92	
			0.08	
			3	
			10, 25, 50	

size, shape, knot size and twist. To estimate standing log prices for each of the log grades considered in our analysis (coastal Douglas-fir grades H, I, J, U, X, and Y), we followed Bogdanski et al. (2023). Better-quality logs producing more value are sawlogs, including grades H and I. Gang, utility or pulp logs, including grades J, U, X and Y, are less valuable. We use standing log price instead of log market prices to avoid the need to account for harvesting costs, which are highly variable based on factors relating to location and terrain. We use price differentials from coastal log market prices and volume shares from BC Timber Sales scaling data from the Harvest Billing System, to determine standing log prices from the average sawlog stumpage rate used in the timber volume analysis. For a detailed description of this approach, see Bogdanski et al. (2023). As with analyses of timber described above, all data were averaged across the four relevant forestry districts for the time period 2010–2020. Log values for the sensitivity analyses were derived using the same volume shares and price differentials applied to the alternative standing timber rates (Table 1).

We used eqs. (1) and (2) above to calculate the log value SEV of unimproved and improved stands, with slight modifications for calculating stand value at rotation. Instead of applying a constant standing timber price to total log volume, we applied individual standing log prices for each grade, to the log volume of the corresponding grade at rotation age.

In our log-grade analysis,  $V_i(T)$  and  $V_u(T)$  were calculated using the following formula:

$$V(T) = p_H v_H(T) + p_I v_I(T) + p_J v_J(T) + p_U v_U(T) + p_X v_X(T) + p_Y v_Y(T) \tag{4}$$

where  $p_i$  is the standing price of log grade  $i$  and  $v_i$  is the volume of log grade  $i$  at rotation age. Incremental log SEV gains were calculated as the difference between value from a stand of genetically-selected trees (selectively bred or ‘improved’) and unselected wild-stand (control or ‘unimproved’) trees, as described in eq. (3).

### 2.5. Monte Carlo sensitivity analyses and economic parameters

All economic parameters are outlined in Table 1. Parameters for our main analyses are considered the “base values”. We also conducted sensitivity analyses using Monte Carlo simulations using the MonteCarlo function from the MonteCarlo package in R (Leschinski, 2019). These sensitivity analyses allowed us to explore how incremental SEV related to varying site productivities and fluctuations in economic parameters for standing timber price, planting cost, incremental seed cost and discount rate, while holding the other variables constant to base values (Fig. A1). To assess alternative outcomes using different parameters, we also explored a range of conditions across sites and initial planting densities under three hypothetical economic scenarios: good, average and poor. These variables and scenarios, and their justifications, are outlined in greater detail below.

Discount rate can strongly affect the profitability of forest investments because it determines how future values are converted into present value (McKenney et al., 1992; McKenney et al., 1989). Higher discount rates can reduce returns and shorten rotations (van Kooten et al., 1995). The base discount rate applied for most analyses was 3%. Bogdanski et al. (2018) indicate 3% is a suitable discount rate for evaluating long-lived investments on Canadian public lands. In our sensitivity analyses, we tested discount rates of 2%, 3%, 4%, 5% and 6%. Lower discount rates were associated with higher incremental SEVs across all sites – i.e., larger differences between genetic gain levels (Fig. A1). However, the size of this effect was much smaller relative to changing timber prices, with incremental SEVs being relatively robust to changes in discount rates as high as 6% (Fig. A1). Because the incremental SEVs among sites were more pronounced at a discount rate of 3% (Fig. A1), this value also seemed appropriate for base analyses to help compare the impact of site qualities as it interacts with genetic gain and

initial planting density. Other research papers exploring economics in forest genetics have applied discount rates over a large range: 1 % (Simonsen, 2013), 2 % (Ahtikoski et al., 2012), 2.45 % (Simonsen et al., 2010), 3 % (Ahtikoski et al., 2018; Ahtikoski and Pulkkinen, 2003; Bogdanski et al., 2018), 4 % (Chamberland et al., 2020; McKenney et al., 1992; McKenney et al., 1989; Tanger et al., 2023), 5 % (Lee et al., 2017; McKeand et al., 2006), 7 % (Kimberley et al., 2015; Petrinovic et al., 2009), and to as high as 8 % (Schreiber and Thomas, 2017). Thus, our range for sensitivity analyses captures the general scope of values reported while the 3 % base value used here reflects an approximate median value found in the literature.

The three hypothetical economic scenarios test varying returns from timber or log prices with fluctuating costs associated with site establishment (seed and planting costs). Average economic conditions are represented primarily by the baseline parameters. As outlined above, average timber and log prices were derived by averaging the inflation-adjusted averages for the period of 2010–2020. In comparison to the baseline scenario, poor economic conditions involve high establishment costs (planting and seed costs) combined with low timber or log prices. In contrast, good economic conditions are composed of low establish-

$$\max_T SEV_{carbon}^i(T) = \frac{V_i(T) - s_0(1+r)^T - e_0(1+r)^T + \sum_0^T \tau(c_t - d_t)(1+r)^{T-t} - \gamma\tau\delta_T}{(1+r)^T - 1} \quad (5)$$

ment costs and high timber or log prices. For timber or log prices, alternative stumpage rates for sensitivity analyses were calculated from the average rates of the 25 % of years with lowest rate, and the 25 % of years with highest rate between 2010 and 2020. Incremental SEV values increased substantially with increasing timber price, and the higher timber prices drew apart differences among sites (Fig. A1).

Establishment costs under a baseline scenario assumed a total planting cost of Can\$1 per seedling. This value is informed by consultations with forestry companies operating in coastal British Columbia, who recommended rounding up from a previously reported cost of \$0.93 per seedling (Wang et al., 2003) to reflect current conditions. We used a per-seedling planting cost in order to accommodate more accurate comparisons between different planting densities. We assume that 90 cents of the 1 dollar establishment cost is for costs incurred at the nursery or due to cold storage, planting, shipping, and administration. We assume the remaining 10 cents is attributable to seed costs, namely, from genetically-selected seed that are commonly deployed. Although this is a simplifying assumption, seed costs can vary based on several factors like seeds per gram, germination rates and organization (BC Ministry of Forests, 2024a, 2024b; BC Ministry of Forests, 2019).

For financial comparisons among genetic gain levels, we also require a baseline cost for wild-stand seed. However, coastal Douglas-fir wild-stand seed are rarely used operationally in low-elevation areas of BC due to seed-use regulations and the successful implementation of the breeding program. Through our consultations, the best recent estimates range from 1 to 2 cents for wild-stand seed. For our base analysis, we therefore assumed wild-stand seed to cost 2 cents, i.e., an 8 cent price discount for wild-stand. Thus, we use a baseline value of 0.92 cents for establishment costs/seedling for wild-stand seed. Projections were robust to changes in planting cost (Can\$/stem) or incremental seed cost (Can\$/stem): Although these costs can affect absolute SEVs, the incremental SEV of timber was consistently higher for better quality sites than lower quality sites regardless of planting or incremental seed costs (Fig. A1).

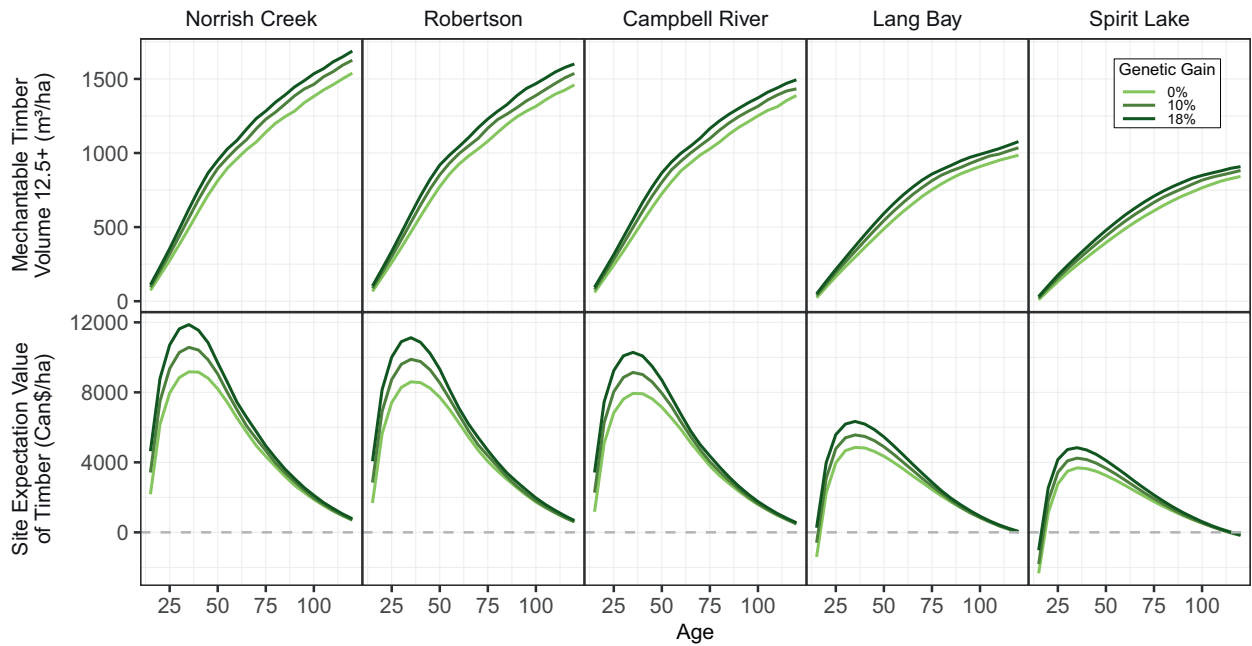
## 2.6. Incorporating carbon pricing into timber and log-grade analyses

Forest carbon projects justify revenue from both timber and carbon credits by leveraging the time value of carbon storage. While stored carbon is ultimately released, delaying release accrues additional credits, as society prioritizes near-term carbon storage for effective climate mitigation. Depending on the specific goals of the land manager, accounting for carbon benefits in economic valuations may or may not be suitable for private landowners or licensees of public land. Most of the existing registries for carbon trading platforms are for private companies (Galik and Jackson, 2009). Foley et al. (2009) indicate that implementing forest-based carbon offset projects on public lands may be complicated by legal, logistical and practical questions. We therefore present SEV with and without carbon for both timber and log-grade analyses. Our method of incorporating carbon values into our discounted cash flow analysis follows van Kooten et al. (1995). When carbon sequestration and timber values are considered together, optimal rotation age for an improved stand and an unimproved stand, respectively, are calculated according to Bogdanski et al. (2023) as follows:

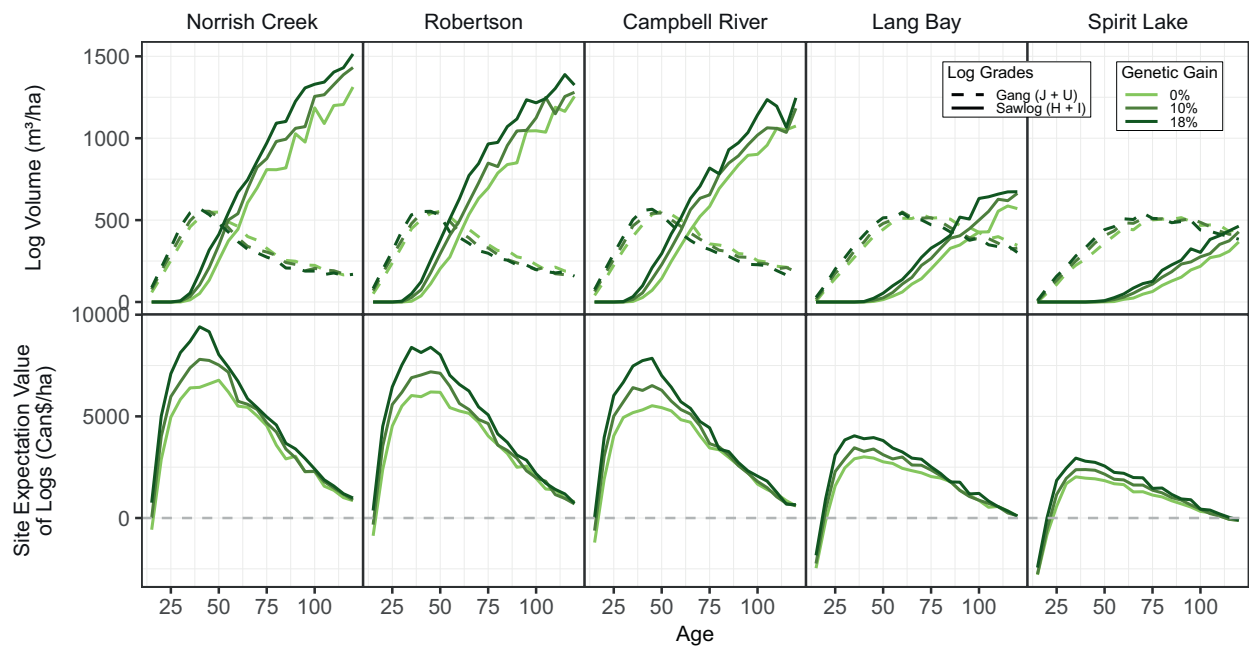
$$\max_T SEV_{carbon}^u(T) = \frac{V_u(T) - e_0(1+r)^T + \sum_0^T \tau(c_t - d_t)(1+r)^{T-t} - \gamma\tau\delta_T}{(1+r)^T - 1} \quad (6)$$

where  $\tau$  is the price of carbon,  $c_t$  is the carbon sequestered in time  $t$ ,  $d_t$  is the carbon released from dead organic matter at time  $t$ ,  $\gamma$  is the proportion of carbon released at rotation age, and  $\delta_T$  is the volume of carbon in live and dead biomass stored in the stand at rotation age  $T$ . The amount of CO<sub>2</sub> equivalent per metric tonne of C from the growth and yield model was converted using a ratio of 3.67 (see, e.g., W. Kurz et al., 2008).

Our analyses assume that all sequestered carbon is released at rotation age. In reality, a portion remains stored in wood debris and harvested wood products. The harvested wood products produced in Canada represent a substantial carbon reservoir, with carbon retained for decades combined with ongoing contributions from harvesting (Kurz et al., 2013; Lemprière et al., 2013). Thus, accounting for longer-term carbon storage in wood products and landfills under a systems perspective would better optimize carbon sequestration strategies (Hennigar et al., 2008; Lemprière et al., 2013). At the stand-level, accounting for the delayed release in these carbon pools would reduce costs, increasing stand value and potentially shortening rotations (Bogdanski et al., 2018; Daigneault et al., 2010; van Kooten et al., 1995). However, accurately modeling carbon release from post-harvest carbon pools can be complex. It is affected by the type of wood product and factors affecting their decay rates as well as disposal approaches (Fraver et al., 2013; Kurz et al., 2009; Lemprière et al., 2013). Excluding substitution effects, where wood replaces carbon-intensive materials like steel or concrete (Geng et al., 2017; Smyth et al., 2017), also incentivizes a reduction in timber harvesting (Haya et al., 2023). Accounting for these interconnected effects are beyond the scope here, yet altogether imply that our simplifying assumption will yield longer optimal rotation ages and lower economic gains than if we had assumed partial delays in



**Fig. 1.** Timber volume and value for genetic gain levels over time at five sites. Timber volume ( $m^3/ha$ , upper panels) and site expectation value of timber (Can\$/ha, lower panels) projected for coastal Douglas-fir stands aged 10–120 years planted with three different genetic gain levels for volume (wild-stand control at 0 % shown as light green, mid-gain at 10 % illustrated by a medium green shade, and top-cross at 18 % displayed in dark green) under an operational planting density (1189 stems/ha) grown at five sites ranging in productivity from high (left) to low (right). Projections were derived from British Columbia’s Tree and Stand Simulator (TASS) growth and yield model calibrated with data from the trial. SEV was calculated using base economic parameters outlined in Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 2.** Log grade volumes and value for genetic gain levels over time at five sites. Log volume by grade ( $m^3$ , upper panels) and site expectation value of logs (Can \$/ha, lower panels) projected for coastal Douglas-fir stands aged 10–120 years planted with three different genetic gain levels for volume (wild-stand control at 0 % shown as light green, mid-gain at 10 % illustrated by a medium green shade, and top-cross at 18 % displayed in dark green) under an operational planting density (1189 stems/ha) grown at five sites ranging in productivity from high (left) to low (right). Although log volumes were modeled for 6 coastal Douglas-fir log grades, to simplify this figure, grades H and I are aggregated as saw logs and grades J and U are aggregated as gang logs. Grades X and Y are not displayed but are included in calculations of SEV. Projections were derived from British Columbia’s Tree and Stand Simulator (TASS) growth and yield model calibrated with data from the trial. SEV was calculated using base economic parameters outlined in Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

carbon release after harvest.

### 2.7. Carbon pricing parameters

Carbon pricing is an important variable but developing a realistic range for sensitivity analyses can be challenging because standards for carbon valuation are not currently well-established. As noted by Romero et al. (1998), carbon sequestration or storage is difficult to quantify monetarily as it is a public good. In our carbon analysis, we use a base price of carbon of Can\$15 per tonne of CO<sub>2</sub>. We also evaluated responses to three additional carbon prices including Can\$10, Can\$25 and Can\$50 per tonne CO<sub>2</sub>. This range of values is justified on the lower-end through the prices reported in the Government of BC’s carbon forestry offset projects (<https://www2.gov.bc.ca/gov/content/environment/climate-change/industry/selling-offsets>): From 2017 to 2021, these provincial prices ranged from just over Can\$7 to Can\$15 per tonne CO<sub>2</sub>. Yemshanov et al. (2005) also indicated that a minimum of Can\$10 per metric tonne of CO<sub>2</sub> was required to make afforestation a financially-attractive investment in Canada – equivalent to just under Can\$15 in 2024. For our mid-range value (Can\$25 per metric tonne CO<sub>2</sub>), comparable estimates have been used elsewhere in the literature (Bogdanski et al., 2018; van Kooten et al., 2019). At the higher end of carbon pricing, van Kooten et al. (2019) used Can\$250 per tonne CO<sub>2</sub>, while carbon prices may rise in the future with limited supply and growing demand (Haya et al., 2023; Sohngen and Mendelsohn, 2003). Therefore, our range from Can\$10 to Can\$50 per metric tonne CO<sub>2</sub> can be considered reasonable.

In practice, carbon price premiums for forestry sequestration projects depend on multiple factors. A key variable is permanence, or the durability of the additional carbon sequestered. As noted by Haya et al. (2023), carbon storage in ecosystems is never permanent; emissions are

simply delayed over the project term. Lower non-permanence risk over the project term can yield higher prices for carbon credits and reduce liabilities associated with carbon storage reversal (Kim and McCarl, 2009; Kollmuss and Polycarp, 2008). Disturbances before term cause a dual financial impact for the land manager due to premature release of carbon requiring repayment and opportunity costs of lost timber revenue. While shorter rotations lower disturbance risks, higher carbon prices can offset these risks, potentially incentivizing longer rotations (Ekholm, 2020). Permanence can be accounted for in carbon markets through discounting (Kim and McCarl, 2009) or buffer pools to mitigate risk (Haya et al., 2023). Carbon pricing also depends on the standards and protocols used to demonstrate additionality, or carbon storage beyond status quo practices, and address risk of leakage, or displaced emissions (Haya et al., 2023): Well-recognized programs requiring third-party validation and verification command higher prices (Kollmuss and Polycarp, 2008). Finally, unpredictable market demand and evolving climate policies will also continue shaping pricing (Kollmuss and Polycarp, 2008). Thus, while our analyses provide insights by modeling a range of carbon prices, they do not capture the full complexity of forest carbon markets.

### 3. Results

#### 3.1. Best timber value & log grades from genetically-selected seed on productive sites

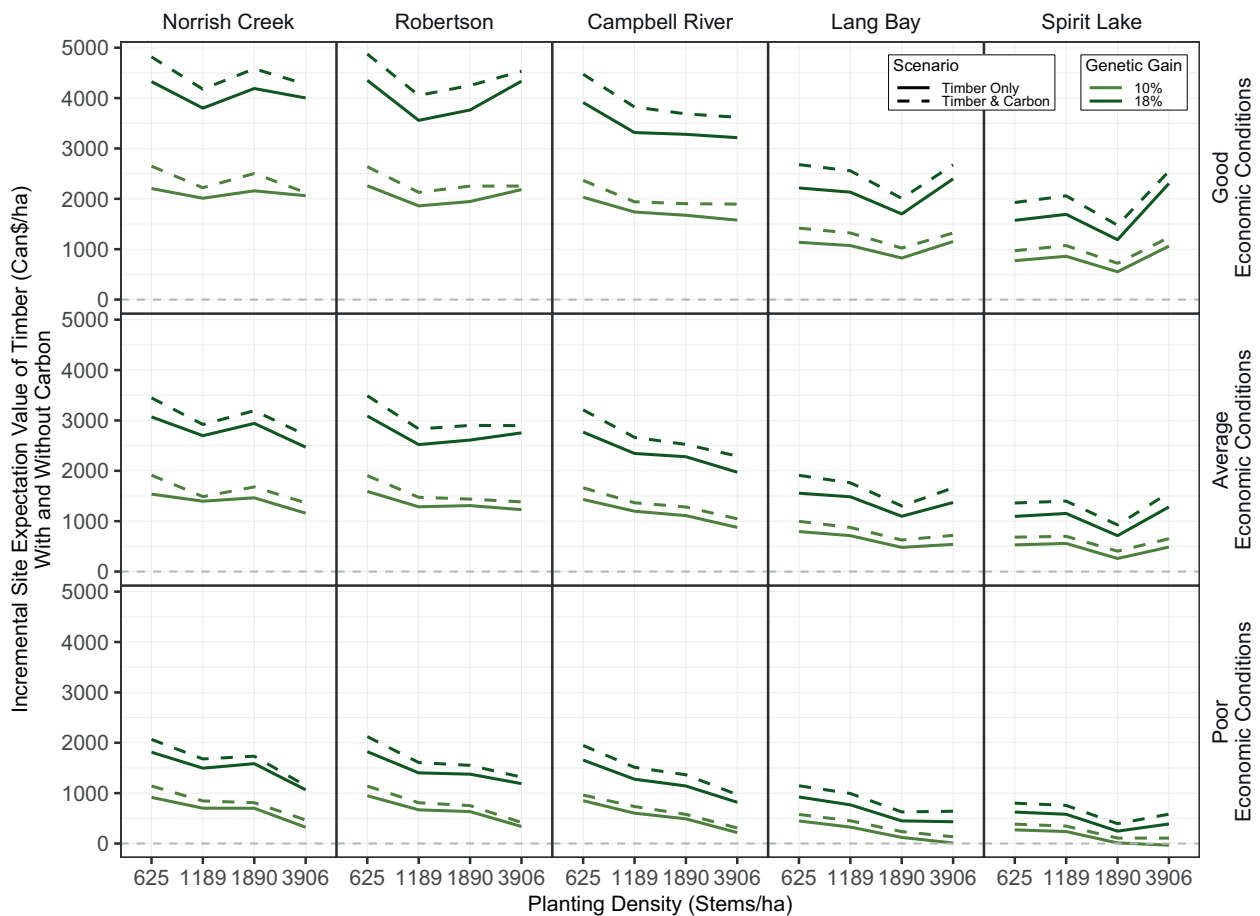
Across all sites and stand ages, stands regenerated with top-cross (18 %) and mid-cross (10 %) genetic gain seed sources were projected to produce substantially greater timber volume than stands regenerated with wild-stand (0 % genetic gain) seed sources (Fig. 1). Greater volume

**Table 2**

Timber and carbon values of genetic gain levels over a range of site productivities. Maximum site expectation value (SEV) and incremental SEV of timber and logs at financial optimal rotation age, with and without carbon (\$15/metric tonne CO<sub>2</sub>), for three levels of genetic gain (0 %, 10 % and 18 % volume gain at 60 years) on five coastal Douglas-fir realized gain trial sites. Values presented are for the base economic conditions (Table 1) and base planting density of 1189 stems/ha. Table cells are coloured to emphasize differences in economic value among treatments, with darker shading indicating higher economic returns. Projections and estimates were derived from British Columbia’s Tree and Stand Simulator (TASS) growth and yield model calibrated with observed tree volumes for each site and initial planting density in the experiment.

Economic Metric	Economic Analysis	Genetic Worth	Norrish Creek	Robertson	Campbell River	Lang Bay	Spirit Lake
SEV (Can\$/ha)	Timber	0%	9,175	8,602	7,940	4,853	3,684
		10%	10,571	9,887	9,138	5,565	4,242
		18%	11,872	11,122	10,284	6,337	4,837
	Timber + Carbon	0%	12,573	11,823	11,043	7,153	5,602
		10%	14,061	13,297	12,408	8,028	6,301
		18%	15,493	14,655	13,708	8,914	7,001
	Logs	0%	6,778	6,199	5,523	3,008	2,025
		10%	7,804	7,189	6,514	3,455	2,383
		18%	9,405	8,397	7,856	4,044	2,946
	Logs + Carbon	0%	10,975	10,230	9,558	6,243	4,657
		10%	12,152	11,582	10,550	6,886	5,259
		18%	13,665	12,839	12,001	7,530	5,915
Incremental SEV (Can\$/ha)	Timber	10%	1,396	1,286	1,198	712	558
		18%	2,697	2,521	2,344	1,484	1,154
	Timber + Carbon	10%	1,488	1,474	1,365	875	699
		18%	2,921	2,832	2,665	1,761	1,399
	Logs	10%	1,026	989	991	447	358
		18%	2,627	2,198	2,333	1,035	921
	Logs + Carbon	10%	1,176	1,352	991	643	602
		18%	2,689	2,609	2,442	1,287	1,258





**Fig. 3.** Economic value of timber from planting genetically-selected seed under a variety of scenarios. Incremental maximum site expectation values (SEV, Can\$/ha) for timber, with and without carbon (Can\$15/metric tonne CO<sub>2</sub>), estimated for multiple scenarios involving deployment of selectively-bred coastal Douglas-fir planting stock. Scenarios include hypothetical economic conditions (upper panels represent good conditions; lower panels represent poor conditions) for four initial planting densities (625 to 3906 stems/ha) at five sites ranging in productivity from high (left) to low (right). Because this illustrates incremental SEV, the mid-gain (10 %) and top-cross (18 %) genetic gain classes are shown relative to the unselected wild-stand control (0 %) as a baseline, represented as a dashed light black line at zero. These incremental gains are estimated by subtracting the maximum possible SEV of the genetically-selected seed sources from the maximum SEV of the wild-stand control, without holding age constant: The maximum SEV of a genetically-selected seedlot might be reached at a different age from the wild-stand control, but the total SEV's were used for their respective time points. Complete model projections by site are presented in Table A1. Projections were derived from British Columbia's Tree and Stand Simulator (TASS) growth and yield model calibrated with data from the trial. SEV was calculated using parameters outlined in Tables 1.

projections were associated with higher site productivity. Compared to wild-stand seed sources, stands established with genetically-selected seed sources were also projected to produce greater log volumes and a relatively greater quantity of higher-quality sawlogs across all sites over time (Fig. 2). Sawlog volume growth was also much greater at the higher productivity sites such that, in addition to having greater total log volume, a larger proportion of total log volume was of sawlog grade around rotation age (Fig. 2). These gains in timber volume and log quality translated directly to higher SEV at financial rotation, illustrated for base parameters in Figs. 1 & 2 as well as Table 2. The most profitable scenarios for both timber and logs involved deploying genetically-selected seed sources at the most productive sites during good economic conditions (Tables A1 & A2). The least (sometimes unprofitable) situations occurred most often by planting wild-stand seed sources at low productivity sites during poor economic conditions (Tables A1 & A2).

Our sensitivity analyses also showed that incremental SEV of timber (Can\$/ha) was most sensitive to changes in timber price as it interacted with site quality (Fig. A1). Higher timber prices increased the incremental SEV of timber more strongly with increasing site productivity: Differences between genetic gain levels across sites were teased apart more strongly with higher timber prices (Fig. A1). As compared to the

results produced using a field-calibrated growth & yield model with higher SI estimates, the simulation-only model using lower SI estimates (method 1) produced similar trends (Figs. A3 & A4). The main difference was lower financial returns (Tables A7, A8 and A9). For example, using our method, predicted SEV for timber in the top-cross group at the most productive site (Norris Creek) at 1189sph was Can\$11,872/ha under a base economic scenario (Table 2). The corresponding value at the most productive site (Robertson) using method 1 was Can\$11,255/ha (Table A7).

**3.2. Incremental gains: Genetic gain produces positive returns over a range of conditions**

Genetically-selected stands were projected to produce greater economic gains relative to wild-stand controls at all sites under base conditions for both timber and logs: Incremental SEVs were positive for both the top- and mid-crosses (Figs. 3 and A2, Table 2). For example, for timber at the 1189 sph initial planting density treatment, incremental SEVs ranged from Can\$2697/ha for the highest-gain stand at the most productive site to Can \$558/ha for the mid-gain stand at the least productive site (Table 2). For log-level analyses at 1189 sph, incremental SEVs were again positive at all sites for both the mid-gain and top-cross

genetic gain classes (Table 2). Incremental SEVs for logs were slightly lower than values in the timber analysis, ranging from Can\$2627/ha for the top-cross stand at the most productive site to Can \$358/ha for the mid-gain stand at the least productive site (Table 2). Genetically-selected seedlots also produced incremental benefits for almost all scenarios tested, including a range of site productivities, initial planting densities and economic scenarios (Fig. 3 for timber, Fig. A2 for logs, and Tables A3 and A4 for incremental SEV values for timber and logs respectively). Where unprofitable situations occurred (Tables A1 & A2), planting genetically-selected seed sources could also offset a portion of the financial losses (Tables A3 & A4). Even at the most extreme negative scenario (3906 sph under poor economic conditions at the least productive site), timber for the wild-stand was valued at –Can\$3063/ha while the top-cross was valued at –Can\$2675/ha (Table A1), for a ‘savings’ (a reduction in losses) of Can\$388/ha (Table A3).

Out of the 120 scenarios tested each for timber and logs (5 sites × 4 initial planting densities × 3 economic scenarios × 2 genetic levels for comparison) using our calibrated models, genetically-selected seedlots produced greater returns compared to wild-stand seedlots in 119 scenarios for timber and 116 for logs (Tables A3 and A4). This represents 99 % and 97 % of scenarios for timber and logs, respectively. For timber, the one exception was for the mid-gain genetic level planted at the ultra-high density (3906 sph) at the least-productive site under the worst economic conditions, which produced –Can \$33/ha less than the wild-stand seedlot. Under the same conditions, however, the top-cross produced a savings of Can\$388/ha. Four exceptions were also observed in the log analyses: For example, the mid-gain and top-cross seedlots yielded respectively –Can\$157/ha and – Can\$32/ha relative to unselected wild-stand seedlots at the poorest site under the worst economic scenario at 1890 sph (Table A4). The other two examples also occur under poor economic conditions, at the ultra-high 3906 sph density at the two poorest sites for the mid-gain genetic level only (under the same conditions, the top-cross seedlots still exceeded wild-stand seedlots). This scenario yielded –Can\$152/ha and – Can\$111/ha less than the wild-stand at Lang Bay and Spirit Lake, respectively (Table A4). Similar patterns emerge for both timber and logs with the re-analysis using lower SI estimates (method 1) but with lower incremental SEVs (Figs. A5, A6). The re-analysis shows incremental gains in 118 scenarios for timber and 115 scenarios for logs (Tables A10 & A11), corresponding to ~98 % and ~ 96 % of scenarios, respectively.

**Table 3**

Wood quality as affected by initial planting density and genetic gain level. Impact of four initial planting densities on wood quality metrics of coastal Douglas-fir at financial optimal rotation age, averaged across five realized gain trial sites, for three different levels of genetic gain for volume (0 % is the unselected wild-stand control, 10 % is the mid-gain group and 18 % is the top-cross group). Favourable wood quality attributes include a lower juvenile wood proportion (crown wood), smaller branches (smaller knots) and lower taper ratio. Table cells are coloured to emphasize differences among treatments, with darker shading indicating worse wood quality metrics. Wood quality projections and estimates to determine optimal rotation ages (earliest age to maximum site expectation value) were derived from British Columbia’s Tree and Stand Simulator (TASS) growth and yield model, with site expectation value being calculated using base economic parameters outlined in Table 1.

Planting Density (sph)	Juvenile Wood Proportion			Branch Thickness (cm)			Stem Taper Ratio		
	0%	10%	18%	0%	10%	18%	0%	10%	18%
625	0.82	0.81	0.81	3.92	3.96	3.93	1.55	1.54	1.53
1189	0.81	0.8	0.81	3.02	3.02	3.02	1.39	1.37	1.37
1890	0.79	0.79	0.78	2.75	2.72	2.74	1.28	1.26	1.26
3906	0.73	0.74	0.74	2.85	2.8	2.89	1.17	1.17	1.18

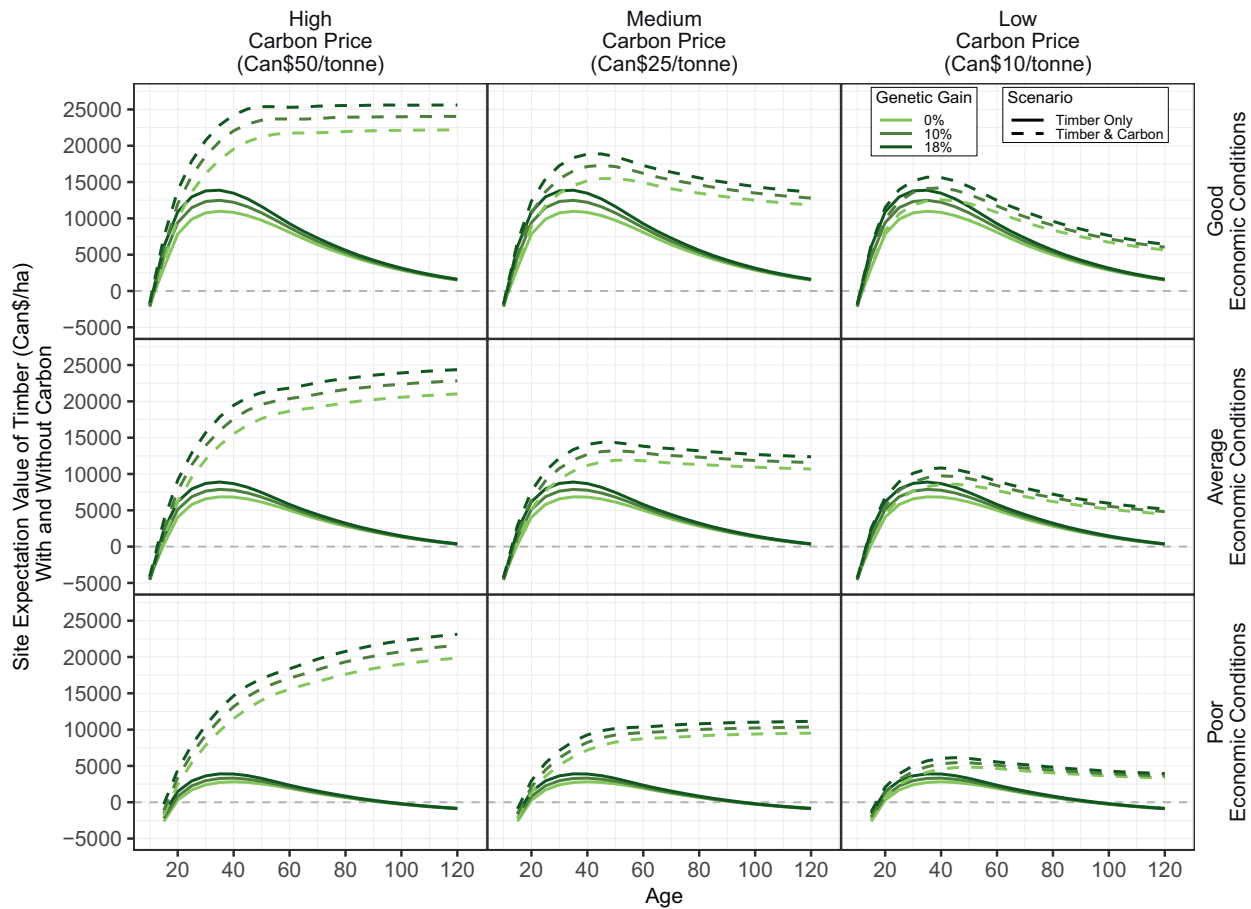
**3.3. Lower initial planting density: Higher modeled returns but lower wood quality**

Generally, lower planting densities yielded higher economic value and incremental returns for planting genetically-selected seed sources (Figs. 3, A2, Tables A1, A2). This trend was more pronounced under average or poor economic conditions, but good economic conditions produced some variability in this overall trend (Figs. 3, A2, Tables A1, A2). Variability in this trend also appears linked to site productivity: At the most productive site, the higher operational planting density (1890 sph) produced greater value than the lower operational planting density (1189 sph) while the inverse is true on the least productive site (Figs. 3, A2). These trends were more variable for the log analysis (Fig. A2) compared to the timber analysis (Fig. 3). Compared to this analysis based on growth and yield models calibrated with observed tree volumes at age 21, the simulation-only exercise (method 1) produced similar but dampened trend for initial planting density. As with our method, there was less variability across planting densities in the timber analysis (Fig. A5) compared to the log analyses (Fig. A6), but planting density was generally less impactful and variable.

Although timber and log-grade analyses simulations generally suggested that lower initial planting densities would yield higher returns, these financial analyses were based on volume only and did not account for wood quality metrics. Initial planting density is known to influence wood quality, which can impact value. At optimal financial rotation age, our growth and yield model suggested that lower initial planting densities consistently produced undesirable effects on wood quality (Table 3). This includes higher proportions of juvenile wood, which has poorer elasto-mechanical properties and can also cause warping. Lower initial planting densities were also associated with larger branches, and therefore larger knots in lumber, significantly reducing value. Lower initial planting densities were further projected to produce trees with more tapered stems, which can reduce lumber recovery. To illustrate using values for the wild-stand control, juvenile wood proportion increased from 0.73 at the highest planting density (3906 sph) to 0.82 at the lowest (625 sph). Likewise, branch size increased from 2.85 cm to 3.92 cm; and stem taper ratio increased from 1.17 % to 1.55 %. All wood quality metric simulations for all genetic gain levels, site productivities and initial planting densities are reported, along with corresponding optimal financial rotation ages, in Table A3. Notably, genetic gain level was predicted to have little effect on these wood quality metrics (Table 3).

**3.4. Incorporating carbon pricing increases value but delays rotation ages**

When carbon pricing is included in the timber and log-grade analyses, the SEV of all treatment combinations increased substantially (Table 2, Fig. 4). Averaging across all sites, for example, the top-cross at 1189 sph without carbon was Can\$8890/ha for timber and Can\$6530/ha for logs compared to Can\$11,954/ha and Can\$10,390/ha when carbon was included (Table 2). These increases were proportionate among genetic gain levels: Incorporating carbon pricing increased value for each group without creating rank changes among the genetic gain classes (Figs. 3, A2). Thus, the genetically-selected seedlots were projected to produce incremental benefits, just as they were without the inclusion of carbon, but the absolute values were higher when managing for carbon as well. When carbon pricing was included, genetically-selected seed sources were projected to produce higher SEVs relative to wild-stand seed sources under all scenarios (Tables A1, A2): Including carbon, incremental gains were projected for all 240 possible comparisons for timber and log-grade analyses. Compared to these results using a growth & yield model calibrated with tree volumes observed at age 21, a re-analysis using an uncalibrated growth & yield model (method 1) produces similar results but SEVs were not as high (Tables A8, A9). The re-analysis also projected positive incremental SEVs for 238 timber and log scenarios (~99 % of scenarios).



**Fig. 4.** Economic scenario analysis for genetic gain levels with timber and carbon. Maximum site expectation values (Can\$/ha) estimated for coastal Douglas-fir stands aged 10–120 years under varying hypothetical economic conditions (upper panels represent good conditions; lower panels represent poor conditions) and carbon prices (Can\$ per metric tonne CO<sub>2</sub>). Three levels of genetic gain for volume are illustrated: The unselected wild-stand control (0 %) is shown in light green, the mid-gain group (10 %) is illustrated by a medium green shade, and the top-cross group (18 %) is illustrated in dark green. Estimates were derived for the low operational planting density (1189 stems/ha) and averaged across five sites ranging in productivity. Complete results for all sites and initial planting densities are presented in Table A1. Projections were derived from British Columbia's Tree and Stand Simulator (TASS) growth and yield model calibrated with data from the trial. SEV was calculated using parameters outlined in Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

On average, genetically-selected seedlots reduce optimal financial rotation age with and without carbon, with stronger impacts of genetic selection under poor economic conditions (Table A6). Generally, the inclusion of carbon value increases rotation lengths, even under the lowest modeled carbon price (Can\$10/t) (Fig. 4). Under a medium carbon price of Can\$25/t, financial rotation ages are extended substantially, but under good or average conditions, it remains financially optimal to harvest within the 120 year range modeled (Fig. 4). Under poor economic conditions (low timber value), however, this is not the case. In the high carbon price scenarios (Can\$50/t), SEV continuously increases over the modeled lifetime of the stand, meaning there is no interior solution for optimal rotation age. In these cases, the increasing amount of carbon sequestered is too valuable to cut down for the 120-year period modeled (Fig. 4). This effect is strongest when carbon price is high but timber value is poor (Fig. 4). Higher timber prices also increase the value of planting seedlots with higher genetic gain (Fig. 4). The re-analysis using the uncalibrated growth & yield model (method 1) showed similar trends (Fig. A7).

## 4. Discussion

### 4.1. Reliable returns projected for genetically-selected seed across sites and planting densities

Tree breeding programs target the most productive species, with Douglas-fir among the top performers in the Pacific Northwest. Our findings show that genetic selection, building on the inherent productivity of Douglas-fir, translates directly into economic returns. Under all economic conditions modeled, genetically-selected seedlots were almost always predicted to provide greater return on investment over unselected (wild-stand) seedlots across a range of sites and initial planting densities: The positive incremental returns projected from planting genetically-selected seed were robust to our economic condition sensitivity analysis. Under the best economic conditions, incremental gains exceeding Can\$4000/ha were estimated for the top-cross plots at the best sites, suggesting that planting genetically-selected seed can lead to substantially greater financial gains. It is worth noting that the estimated level of genetic gain for the top-cross plots is comparable to the genetic gain of operational seedlots currently being produced in orchards.

The best returns for planting genetically-selected seed were observed at the most productive sites – as expected given similar findings elsewhere (e.g., Chamberland et al., 2020; Chang et al., 2019; Dash et al.,

2019; Lee et al., 2017; McKeand et al., 2006; McKenney et al., 1992; McKenney et al., 1989; Petrinovic et al., 2009). Notably, even on the lowest-quality sites and under the worst economic conditions tested here, all stands established with genetically-selected seed sources under operational planting densities (1189 sph) were estimated to have positive, albeit smaller, timber and log SEVs. Although negative SEV for both timber and logs occurred in the non-operational, most extreme initial planting density (3906 sph) under the worst economic scenario at all sites, planting genetically-selected seed sources almost always offset a portion of the financial losses, leading to incremental benefits. Thus, although we find that benefits are maximized on more productive sites, paying up front for higher gain seedlots remains viable even under poor economic conditions and on the least productive sites modeled. Such consistently higher returns from planting genetically-selected seedlings can further reduce susceptibility to unexpected timber market fluctuations (Serrano-León et al., 2021).

Very few exceptions occurred where wild-stands produced higher SEVs compared to genetically-selected stock: For both timber and log-grade analyses without accounting for carbon crediting, this amounts to 5 times out of 240 comparisons or about ~2 % of scenarios. These occurred under the worst economic scenarios for the poorest-quality sites at the highest planting densities. These exceptions could be due to stochasticity in the model outputs or potentially a real interaction. If the latter, it could be due to the poor economic conditions being unable to compensate for the higher planting costs from more expensive orchard seed carried through to rotation. The overall weight of evidence from all simulations suggests, however, that genetically-selected seed can be expected to produce higher return on investments under most of the conditions tested (~98 % of the modeled scenarios without carbon pricing). Here, the consistent benefits from planting genetically-selected seedlings across this range of sites, initial planting densities and economic scenarios also highlights the value of historic tree breeding efforts.

#### 4.2. Sustaining wood quality values in genetically-selected Seedlots

Genetic gain level was predicted to have little effect on wood quality metrics. The models do not expect genetically-selected planting stock to inherently lead to reduced wood quality. These model predictions are corroborated by non-destructive wood-quality proxy data from the same coastal Douglas-fir realized gain trial (Isaac-Renton et al., 2020): Wood quality in the higher genetic gain classes was slightly reduced, but the effects were comparatively minor (-1.1 to -4 %) relative to the large (29 %) volume gains observed. Furthermore, the realized gain experiment was established in 1996 with the sole objective of evaluating growth gains. The families used in the trials were not chosen to provide balanced representation of wood quality in the breeding population, whereas wood quality is carefully managed in tree breeding programs and seed orchards.

Though genetic gain in volume is not directly associated with a reduction in wood quality, log and lumber value may be indirectly affected (positively or negatively) through stand-management decisions. Faster-growing families do not inherently have worse wood quality, but if they are harvested earlier, they will have a greater proportion of juvenile wood. This also aligns with a general trend in the forest industry transitioning to harvesting second-growth forests under shorter rotations with higher juvenile wood proportions that reduce wood quality and value (Aubry et al., 1998; Fahey et al., 1991; Kennedy, 1995). Managing wood quality as a selection criterion will also become increasingly important as climate conditions associated with lower wood quality in Douglas-fir are expected to become more prevalent in coastal areas (Stoehr et al., 2009). For these reasons, the importance of maintaining wood quality values for high-quality timber species is well-recognized by provincial tree breeders. Due to negative genetic correlations with volume (Ukrainetz et al., 2008), however, these values are often included as a secondary selection criterion in a two-step analysis

(Howe et al., 2006), with wood quality traits being used to screen selections made for volume, the primary trait.

Quantifying the value associated with breeding efforts related to wood quality is challenging. Incorporating wood quality metrics into financial analyses relies on understanding how wood properties affect end-use products and their market value, which can change by client and over the long rotations in forestry (Ahtikoski et al., 2018; Aubry et al., 1998). Although we are unable to capture financial impacts of specific wood characteristics, we built on the traditional timber analyses to partially capture some of these effects as they relate to piece size through a valuation of log volumes. The log analysis estimated the output of stands by volume of log grades instead of by total merchantable timber volume and applied individual prices per log grade. This allowed us to consider additional gains or losses in the value of improved stands that derive from changes in the shape and size of individual trees that might not be fully reflected in total stand volume. From a genetics and silviculture perspective, the trends for logs and timber were similar. However, on average, the log analyses estimated lower SEVs than the timber analysis. The log analyses may provide a more conservative estimate of stand value overall because each log grade is priced differently, ranging from Can\$12/m<sup>3</sup> to Can\$67/m<sup>3</sup> (Table 1). Values will be lower than using a simple undifferentiated merchantable volume times average stumpage value (base timber price is Can\$40/m<sup>3</sup>), given the significant proportion of gang log (J, U) and pulp log (X, Y) grades. This suggests that a timber volume approach to measure SEV could be overestimating the value of stands. This may be especially true at the lower initial planting densities, where wood quality may be of greater concern.

#### 4.3. Initial planting density: Independent silviculture decision to balance volume and quality

Our analyses did not detect interaction effects between initial planting density and genetic gain level that could lead to unexpected financial outcomes. In other words, the positive returns from deploying genetically-selected seedlots at lower initial planting densities seemed to be additive. Therefore, selecting the most appropriate initial planting density is less of a decision regarding the best deployment of genetically-selected seedlots and rather a silvicultural decision that can be considered independently. Although Dash et al. (2019) did not consider initial planting densities during reforestation, as we did here, their analyses on post-thinning stand-density in *Pinus radiata* in New Zealand also showed that there was no significant interaction between resulting stand density and genetic gain of seedlots. As with our analyses, these authors indicate these effects can be considered independently. To maximize financial returns, therefore, the best quality sites may warrant the most silvicultural investment – in terms of both seedlot and stand density management.

One potential reason why lower initial planting densities were projected to produce higher economic returns is because planting costs per tree can be substantial: lower initial planting densities lead to lower upfront costs and these savings can be carried forward to rotation. Lower inter-tree competition at lower initial planting densities can also produce higher returns because trees can grow larger more quickly with more initial growing space. However, it is important to reiterate that wood quality metrics were not incorporated into our financial analyses directly. For example, branch diameter is known to significantly reduce value of Douglas-fir lumber (Aubry et al., 1998; Lowell et al., 2014). In turn, thicker branches occur at the lowest initial planting densities - predicted by the models here and observed by Isaac-Renton et al. (2020). Therefore, the higher SEVs at lower initial planting densities do not reflect the wood quality losses associated with lower planting densities – which may have a significant impact at the point of sale, depending on future markets. An additional factor not considered here is the cost of increased site maintenance associated with lower initial planting densities. In areas of high brush hazard, or where ingress from

other non-target tree species is substantial, the costs of mechanical or chemical brushing could quickly outstrip any increases in stand value. Judgement and experience of the practicing forester are needed to balance these different values associated with initial planting density.

#### 4.4. Carbon pricing may improve returns but complexity and risks may limit adoption

Due to their productivity, Douglas-fir forests of the Pacific Northwest are some of the most efficient at sequestering carbon per unit area (Foley et al., 2009; Galik et al., 2022). When companies are financially incentivized to incorporate carbon dynamics in their management portfolio through increasing carbon pricing, managing forests to include carbon value may become more attractive in an already productive region. We found that including carbon pricing leads to larger financial benefits, and genetically-selected seed sources incorporating carbon outperformed wild-stand seedlots 100 % of the time for all scenarios simulated with a growth & yield model calibrated with trial data. As the financial incentive to enhance uptake of carbon increases, substantially more value is predicted for scenarios incorporating carbon pricing rather than timber or log analyses alone. Further increasing productivity with genetically-selected seed may thus be a good approach to maximizing benefits, especially when combined with the additive effects of site quality and an appropriate initial planting density. The benefits of including carbon were strongest at the most productive sites, especially with higher carbon prices. At the same time, however, the additional carbon revenues might help offset negative returns on poor sites under poor economic conditions.

Incorporating carbon values also extended financial rotation ages. This has been widely observed in numerous studies (e.g., Asante and Armstrong, 2012; Brêteau-Amores et al., 2023; Couture and Reynaud, 2011; Daigneault et al., 2010; Dwivedi et al., 2009; Ekholm, 2020; Foley et al., 2009; Lee et al., 2017; Plantinga and Birdsey, 1994; Romero et al., 1998; van Kooten et al., 2019; van Kooten et al., 1995). Some counterexamples exist, however (e.g., Huang and Kronrad, 2006). In our study, we used a constant carbon price rather than one that continues to rise with increasing urgency to limit temperature rises, which can affect rotation lengths (Ekholm, 2016). Using this approach, we found that higher carbon prices also led to greater differentiation among financial returns from genetic gain levels – especially when timber prices were also high. However, when timber prices were low enough, and carbon prices were high enough, we found it was not economically optimal to harvest stands from any genetic gain level within the modeled 120 age range. In such scenarios, sequestration under a high carbon price caused stand value to continuously increase. Thus, carbon pricing could potentially serve as justification for plantations that are not economically viable in terms of timber alone on sites less productive than those considered in this study.

As a note of caution, our analyses did not incorporate disturbance probabilities. While higher carbon pricing incentivizes longer rotations, this also increases risks of impermanence and associated financial penalties due to rising biotic and abiotic disturbances under climate change (e.g., Dye et al., 2024; Galik and Jackson, 2009; Kurz et al., 2008; Lindroth et al., 2009; Reichstein et al., 2013; Seidl et al., 2017; Zhao and Running, 2010; Zhou et al., 2019). For example, climate-driven wildfires have already become more common in the western US (Abatzoglou and Williams, 2016; Westerling et al., 2006) and interior of British Columbia (Parisien et al., 2023), with risks predicted to increase substantially (Anderegg et al., 2022; Wasserman and Mueller, 2023). Risks are also likely to rise even in inherently less fire-prone coastal temperate ecosystems of BC (Parisien et al., 2023). Given these growing risks, reducing rotation ages may be a compelling means of reducing financial liabilities while managing forests for carbon (Couture and Reynaud, 2011; Daigneault et al., 2010). Therefore, an increasing probability of disturbances like fire serves to counteract the lengthening of rotations associated with higher carbon prices (Couture and Reynaud, 2011;

Daigneault et al., 2010). Yet when carbon prices are high enough, they could offset financial risks of reversal so that longer rotations remain viable for managing carbon despite fire risks (Daigneault et al., 2010; Ekholm, 2020). A balance between these two factors thus influences optimal rotation ages. If we had incorporated fire risks, the longer rotations observed here may have been shorter. At the same time, navigating this ‘carbon price / fire risk frontier’ is complex as it is also influenced by land manager’s risk aversion (Couture and Reynaud, 2011).

Impermanence risks could also be managed through carbon programs offering temporary contracts to landowners, i.e., a carbon rental payment approach that allows managers to postpone harvest to engage in offset programs without greatly increasing exposure to impermanence risks (Daigneault et al., 2010; Tanger et al., 2023). Additional and interacting considerations include silvicultural methods that balance carbon storage and timber yields as they interact with disturbance risks, like thinning operations or stand diversification. Periodic thinning and longer rotations are effective approaches for managing timber and carbon in Douglas-fir forests in the Pacific Northwest despite disturbance risks (Daigneault et al., 2010). Our analyses are also limited to a single-species, even-aged system. Diversifying stand structure from single to multiple canopy layers can take decades (D’Amato et al., 2023), with lead times that would be challenging to model here. However, while diversifying stand structure and species composition could reduce impacts of disturbances like droughts under some conditions, diversity does not always reduce vulnerability to drought (Grossiord, 2020; Grossiord et al., 2014). Under forest diversification, the impacts of drought and windstorm damage on timber volumes, economic return and carbon sequestration also appears sensitive to discount rates and climate change scenarios (Brêteau-Amores et al., 2023).

Risks of impermanence could be further reduced by selecting site-suited tree species resilient to disturbances, a key silvicultural decision. Species with a higher potential for sequestering carbon, which are especially incentivized with higher carbon prices, could help offset financial liabilities associated with the risk of reversal (Ekholm, 2020). Douglas-fir has a high potential for sequestering carbon, as noted by several authors (Daigneault et al., 2010; Foley et al., 2009; Galik et al., 2022), and our results show that planting genetically-selected Douglas-fir seedlots could further offset liabilities due to greater values. Our results also suggest that planting genetically-selected trees could reduce rotations and exposure to disturbance, as also suggested elsewhere (e.g., Howe et al., 2006; Serrano-León et al., 2021). Thus, planting genetically-selected seedlots could further reduce impermanence risks and potentially increase carbon prices.

Our analyses did not consider the value of carbon storage of end-products after harvest. Our analyses assumed that, at harvest, the full amount of carbon sequestered by the forest would be released. Although much carbon is expected to be released shortly after harvest (Ekholm, 2020; Plantinga and Birdsey, 1994), some carbon can be stored for longer periods in harvested wood products (Johnston and Radeloff, 2019; Kurz et al., 2013; Lemprière et al., 2013). Thus, assumptions of carbon storage in harvested wood products can impact the net carbon balances as well as rotation ages (Bogdanski et al., 2018; Daigneault et al., 2010; Dymond, 2012; Galik and Jackson, 2009; Metsaranta et al., 2011; Smyth et al., 2020; van Kooten et al., 1995; Xu et al., 2018). Real-world returns can be highly variable depending on the region and carbon accounting methodologies used (Foley et al., 2009), so the implications of our results may not be widely transferrable to other forest types. Finally, practical challenges may also be a barrier to entry in emerging carbon markets (Galik and Jackson, 2009). Barriers can be financial and operational, as implementation costs can be substantial, and comprehensive assessments require significant time and expertise, while uncertainty can amplify these challenges (Galik et al., 2022; Galik et al., 2012; Kollmus and Polycarp, 2008).

#### 4.5. Robustness of results with differing growth & yield approaches

Our study demonstrates that the primary findings regarding the economic benefits of using genetically-selected seedlots are robust using two different growth & yield methodologies. The main manuscript presents results based on a calibration of the growth & yield model with observed tree size values from a realized gain trial to refine predictions, as has been recommended for modeling financial gains associated with genetic gains (Serrano-León et al., 2021). To test the robustness of these findings, however, we re-ran the analyses using a simulation-only exercise that relies solely on TASS model assumptions and predictions for genetic worth across planting densities using height-based site productivity estimates (method 1). Minor differences emerged. For example, the re-analysis with method 1 showed slightly reduced financial returns, as would be expected given lower site index estimates under this approach. The impact of initial planting density on stand performance, while showing generally similar trends, seemed less impactful and showed less variability. This is also to be expected as the calibrated method is based on an average across two replicates per site and planting density combination, while TASS simulates a broader, more generalized average. This underscores the reasoning behind the original approach informed by the field data, but altogether, the re-analysis reinforces the core conclusion that genetically-selected seedlots enhance economic outcomes and carbon sequestration potential.

#### 4.6. Managing for multiple values crucial for tree breeding under uncertain futures

Although the growth and yield model was calibrated to age 21 with real-world data, there are inherent uncertainties with all models – especially as simulations project further into the future. This is especially true under rapid climate change, as models were trained on historic climates and observations. Climate change could reduce overall forest productivity, lowering economic returns. Ideally, planting selected seed could offset some of these losses. Tree breeders are responsible for ensuring their selections can cope with a warmer and more variable climate so that planted forests can continue producing volume gains, financial returns, and a suite of ecological, social, cultural and carbon-sequestration services. These forest genetics programs are now working to screen tree breeding populations for adaptive traits to enhance resilience to climate warming and extremes like drought, heat and frost. Tree breeders are also evaluating their breeding populations for higher tolerance to insects or pathogens of increasing concern under climate change. The province's forest genetics programs are also helping to maintain forest health, productivity and value by carefully managing wood quality, general adaptability and genetic diversity. The aim is to select generally good performers rather than the optimal seedlot for a specific or narrow range of circumstances (Evison and Apiolaza, 2014) – biologically or financially. Managing for multiple traits in tree breeding programs is crucial for helping foresters continue managing for timber and carbon as well as multiple other values across the landscape, especially under uncertain futures.

Thus, although our analyses consider economic value of genetic gains from the land-managers perspective, evaluating costs and benefits from a program perspective would be a useful area of research under uncertain futures. This could consider fixed research costs for breeding, testing and selections for novel traits as well as potential variable operational costs for modifying ongoing production capacity (e.g., orchard production). This could also consider the expected added value of planting seedlots tolerant to biotic or abiotic stressors, including genetic gain levels and changing areas of deployment under climate change. Our analyses show that historic tree breeding has led to substantial higher value already. Therefore, it seems likely that ongoing investment in improving forest productivity, health, quality and diversity will become increasingly important and financially incentivized as damages increase under climate change.

## 5. Conclusions

Our simulations suggest that planting coastal Douglas-fir with higher genetic gains for volume will reliably yield higher returns on investment relative to planting wild-stand (unselected) seedlots. With very few exceptions, the positive incremental returns obtained from deploying genetically-selected seedlots were consistently sustained across a range of scenarios testing multiple site productivities, initial planting densities, economic scenarios and carbon pricing. The highest benefits accrue at the most productive sites under the best economic conditions. Although lower operational planting densities generally increased the absolute value of stands at financial rotation, planting density does not affect incremental gains from deployed selected planting stock: The lack of interaction suggests that initial planting density can be considered as an independent silvicultural decision from genetic gain. Incorporating the costs and benefits of carbon sequestration (or release) through variable carbon pricing scenarios increased the value of the stands, particularly at the least productive sites when timber prices were low. Although rotation ages were extended and value was higher even at low carbon prices, there were no unexpected interactions with genetic gain levels: Planting genetically-selected seedlots was more valuable than planting unselected seedlots, with or without carbon pricing.

The overall consistency of financial gains suggests that planting genetically-selected seed is a good financial investment for Douglas-fir in the mild temperate coastal ecosystems of British Columbia. These financial gains are additional to other anticipated benefits from using seedlots derived from tree breeding programs, which are managed for multiple desirable traits such as wood quality, pest resistance, and, more recently, climate-adaptive traits. The consistent benefits from planting genetically-selected seedlings across a range of site productivities, multiple initial planting densities and diverse economic scenarios also highlights the value of historic tree breeding efforts and the need for ongoing investment to adapt these programs to changing climates.

#### CRedit authorship contribution statement

**M. Isaac-Renton:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **B. Moore:** Formal analysis, Investigation, Methodology, Writing – original draft, Visualization. **J. Degner:** Writing – original draft, Writing – review & editing, Data curation, Validation. **C. Bealle Statland:** Data curation, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **B. Bogdanski:** Methodology, Resources, Writing – original draft, Writing – review & editing, Supervision. **L. Sun:** Methodology, Supervision, Validation, Writing – original draft, Resources. **M. Stoehr:** Conceptualization, Data curation, Writing – original draft.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary results complementing this article can be found online at <https://doi.org/10.1016/j.forpol.2024.103397>.

## Data availability

Data will be made available on request.

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