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An economic analysis of management practices to mitigate butt rot and deer browse of planted western redcedar

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ABSTRACT

We consider the economic feasibility of silviculture investments to reduce butt rot (through stump removal) and ungulate browse damage (stand establishment strategies), which are the most serious impacts to planted western redcedar (Thuja plicata Donn ex D. Don) stands in coastal British Columbia, Canada. We find mixed support for these investments, even if carbon sequestration benefits are included. We do find butt rot causes significant material damage to volumes, but such damage tends to occur well into the future of the stand diminishing the negative impact on stand value. As such, given the high costs of stump removal, and despite losses of high-quality logs, we find little support for stump removal except under very low discount rates (2%). Deer browse impacts are found to occur in the early stages of stand development, and projected stands should sufficiently recover volumes and value by harvest age. However, under positive carbon prices, because deer browse mitigation measures have an immediate impact on biomass accumulation in the early stages of stand development, we find some conditions for which low-cost deer browse mitigation options might be economically supported on forestlands. Finally, we found that increased planting of seedlings is likely a low-cost, financially attractive option under a broad set of conditions, even on sites without risk to damage, meaning a possible no-regrets strategy to mitigate damages from either deer browse or decay. The benefits of planting highlight the feasibility of using tree breeding to increase growth, resistance to deer, decay, and drought. The methods developed in the paper to evaluate the impact of both root rot and ungulate browsing could be applied to other ecosystems elsewhere.

Keywords

butt rot, carbon, deer browsing, economics, forest management, Monte Carlo simulation, western redcedar, plantations

Citation

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INTRODUCTION AND BACKGROUND

Western redcedar (Thuja Plicata Don ex D.Don), while not a true cedar but a member of the cypress family Cupressaceae, is widely abundant in parts of British Columbia (BC) and is the provincial tree of BC. Its natural range extends from southeastern Alaska to northern California, mainly along the Pacific coastal region but also within a narrow, wet belt of interior BC and the states of Washington, Oregon, and Idaho. An individual tree can live for hundreds of years and reach 60 m in height, with diameters between 150 cm to 300 cm (Parish and Thomson 1995). Although western redcedar (WRC) is long-lived, it is also highly susceptible to infection from fungi. Such infections often lead to butt rot and a considerable loss in wood volume among harvested trees. Conversely, WRC is known to be lightweight, highly durable, and rot resistant when in service, making it one of the most prized commercial species. These properties of WRC make its wood a valuable material for many in-service uses, such as roofing, utility poles, fencing, siding, and decking materials. Also, WRC wood fibre is used to make specialty pulps for surgical drapes, masks, and gowns (Gonzalez 2004). In addition to commodity uses, the wood, bark and branches play a major role in the traditional culture of indigenous peoples of western North America.

Despite the significant economic importance of WRC, total volume harvested declined 38% between 2003 and 2022 (BCMF 2023). This trend is in part due to a declining available inventory, both on private and public land (i.e., crown land), as harvests on the coast transition from high-volume, old-growth stands to second-growth stands. Further reductions to the amount of available inventory on crown land have been the result of increased land conservation efforts which have focused on protecting old-growth stands. These trends have prompted forestland managers to seek ways to increase future timber supply on the still available land by moving towards more active management of WRC, including establishing WRC stands through planting rather than through natural regeneration (Antos et al. 2016). However, concerns regarding damage from deer browse (Vourc'h et al. 2002) and various root and butt rots have led to concurrent adoption of management practices to mitigate impacts. The fungi causing root and butt rot include about 15 white and brown rot fungi with Obba rivulosa (Berk. & M.A. Curtis) Miett. & Rajchenb. common on the coast and Phellinus weirii (Murr.) Gilbn. common in the BC interior (Sturrock et al. 2017).

Planted and naturally established western redcedar stands are quite productive on good growing sites, with mean annual increments of (MAI) of 10 to 20 cubic meters (m^3) per hectare per year. On the average growing site, western redcedar stands may have a steady growth trajectory with maximum current annual increment at approximately 82 years of age and maximum MAI around 130 years of age (Burns and Honkala 1990). Forest management strategies that aim to maximize wood supply by harvesting stands at MAI are likely to result in yields that are lower than expected, given the significant amount of stem decay that is frequently found in stands of this age (Buckland 1946; van der Kamp 1975; 1986). In the context of timber supply, decay is a primary cause of cull in old-growth WRC stands, resulting in increased harvesting costs and often significantly reduced net volumes (Buckland 1946; Kimmey 1956; Renzie and Han 2001). One of the main silvicultural strategies used to control root and butt rots is through the removal of stumps following harvest. While stumping can be effective, it comes at a high financial cost that may dissuade some silviculturalists from using this strategy (Bogdanski et al. 2018). In terms of establishing second-growth stands of WRC following harvest, one of the main challenges is limiting the damage or loss caused by browsing by ungulates (black-tailed deer [Odocoileus hemionus columbianus] and Roosevelt Elk [Cervus elaphus roosevelti]) in coastal ecosystems (McNay and Doyle 1987; Booth and Henigman 1996). The use of plastic tubes, cages, meshing and development of browse-resistant seedlings have helped to increase regeneration success, but these incremental costs are significant (Stein 1997; Henigman and Martinz 2002).[1]

Very few studies have focused on the economic impact that disease, such as butt rot, can have on commercially important tree species, like WRC. Even fewer studies have examined economic impacts due to ungulate browse, and an extensive search of the peer-reviewed literature revealed that no studies have looked at the combined effect of disease and browse. Self and MacKenzie (1995) conducted an economic analysis of stumping for the management of Armillaria spp. in second-rotation Pinus radiata in New Zealand and found a high net economic benefit to the practice, even with high discount rates. However, because the study used gross log values and did not account for harvesting and transportation costs, it is likely that the benefits attributed to stumping were inflated. Russell et al. (1986) found stumping significantly reduced damage from

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[1] Taisa Brown, 'Efficacy of MIFO Elk Silviculture Strategies', Presentation to the Coast Silviculture Committee, February 2018. Available at: http://www.coastalsilviculturecommittee.com/uploads/4/4/1/8/4418310/john_andres___taisa_brown_-_elk_damage_in_the_campbell_river_area.pptx

Phellinus sulphurascens in a coastal Douglas-fir (Pseudotsuga menziesii) forest in Washington State. On highly productive sites, they found stumping to be profitable and a better option than not stumping. Brunette and Caurla (2016) compared different treatments to control Heterobasidion annosum, a fungus that has caused significant losses within stands of Pinus pinaster in coastal regions of France. Following harvest, they found that the removal of stumps showing signs of fungal infection generated higher land expectation values when compared to other treatments, including the use of chemicals, the removal of all stumps (regardless of infection), and leaving the stand fallow for five years before replanting. More recently, Bogdanski et al. (2018) studied the economic benefits of stumping to control Armillaria spp within stands of planted Douglas-fir (Pseudotsuga menziesii). While they found stumping financially attractive on highly productive sites under average economic conditions, its use on moderately productive sites was only attractive if both carbon and timber values were considered.

With regard to damage from ungulate browsing, one of the few reported studies looked at height growth losses of heavily browsed Douglas-fir stands (Mitchell 1964). A cursory, stand-level, economic analysis of one of the most heavily browsed sites suggested that impacts to tree quality or volume would be small by the time the stand was scheduled to be harvested, reflecting the ability of Douglas-fir to recover following physical damage. Ward et al. (2004) investigated the cost of Capreolus capreolus (row deer) on Sitka spruce forest in Britain. Their analysis looked at the change in calculated net present value of a stand over one rotation due to reduced height growth from browsing by roe deer. Damage from browsing was modelled by imposing a one to four year delay in terms of when the stand could be harvested. Results showed that the expected stand net present value fell quickly with every year the harvest was delayed. However, because the authors used static yield tables to obtain estimates of volumes, they were unable to account for the compensatory growth that occurs once browsing has stopped. As such, it is likely that their results overestimated the impact caused by ungulate browse.

Greiss et al. (2015) investigated the benefits of establishing WRC together with Douglas-fir, given that the latter species is less palatable to ungulates. Their results indicated that the optimum mixture of Douglas-fir to WRC is 25:75, but only if protective measures against deer browsing are employed. If no protective measures are used, then a ratio of 75:25 was preferred. A similar study by Clasen et al. (2011) looked at the optimum mix of Norway spruce (Picea abies [L.]) and European beech (Fagus sylvatica L.) to decrease the financial risks due to ungulate browsing in central Europe. Similar to Griess et al. (2015), their results showed that using a mixture of species can effectively reduce the financial impact caused by deer browsing.

Although these studies have contributed to our understanding of the economic impacts caused by disease and ungulate browsing on important commercial tree species, several questions remain unanswered. For example, few listed studies considered a broad range of economic conditions, while even fewer incorporated the added effect of managing stands for carbon value. Therefore, the current study aims to investigate the economic (financial) performance of silviculture investments to enhance WRC by planting, and by mitigation of butt rot and deer browsing by black-tailed deer.[2] We simulate numerous forest and economic conditions to capture the range of circumstances forest managers might face in coastal BC. Next, we introduce probability analysis of future timber prices to explore the possible range of expected outcomes better. Specifically, we use this analysis to determine if there is any economic support for root and stump removal to control for butt rot. Likewise, the analysis is used to determine if there is any economic support for using ungulate protective measures, including browse-resistant seedlings, higher initial planting densities, and protective tubes. Finally, we consider how carbon value inclusion may influence economic support for such mitigation measures. The approach developed in this paper can be extended to other ecosystems and regions impacted by butt rot and deer browsing.

DATA AND METHODS

We consider the Coastal Western Hemlock biogeoclimatic zone of BC as the study site (Meidinger and Pojar 1991). While the interior cedar-hemlock biogeoclimatic zone also supports WRC, the productive quality of the sites are generally lower than the coast, and so we expect the coastal analysis should extend to this region as well.[3] We evaluate the economic impacts of decay and deer browsing on WRC in the coastal area, where such damage has been known to be a significant management issue. For ungulate damage analysis, the growth and yield analysis is augmented with

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[2] Black-tailed deer are more common across the coastal forest region and so were chosen for the analysis in this study (http://www.env.gov.bc.ca/wld/documents/muledeer.pdf). However, Roosevelt Elk can potentially cause greater damage to a planted stand of WRC than what is modelled here (http://www.env.gov.bc.ca/wld/documents/elk.pdf)

[3] We did conduct analysis of the interior region and as expected, the results were very similar to the coast analysis across the range of common site productivities.

simulation modeling of possible deer damage on hypothetical WRC stands. The methods used generally follow those used in Bogdanski et al. (2018) to investigate decay impacts and mitigation efforts on Douglas-fir plantations in the interior of BC. This involved using well established discounted cash flow analysis (see Klemperer (1996) to determine the land expectation value of a stand at time of establishment. The method accounts for the stream of timber or timber and carbon revenues (if applicable) over an infinite planning horizon and successive rotations. However, unlike Bogdanski et al. (2018) the method is extended to more detailed timber valuation by explicitly accounting for log quality production, deer browse impacts on stand growth and yield, and the introduction of probabilistic models of future timber and carbon retention at time of harvest to better account for the uncertainty of these key economic parameters. The consideration of a broad range of discount rates in the analysis is used to reflect the different rates of time preference or costs of capital that a public and private landowner faces in practice.The exact steps of the methods and data used are detailed below.

Decay and deer impacts and growth and yield models

Growth and yield modelling

Following Bogdanski et al. (2018), current and future merchantable volume and forest biomass was estimated using the Tree and Stand Simulator (TASS) for all coastal sites. TASS is a biologically oriented spatially explicit individual tree growth model (Di Lucca 1999) used to project stand yield per hectare for managed stands in BC. Future merchantable timber volume and stand biomass, including whole tree biomass and dead organic matter, was projected forward to age 120 using TASS. To model a range of site productivity, we consider site indices of 20, 25, 30 and 35 metres at breast height age 50. Stand simulations were initialized at common operational initial planting densities of 800 and 1000 stems/ha using 2-year-old stock, with the higher density representing one of the possible mitigation strategies against deer browse impacts.

TASS estimates living and dead biomass in tonnes of dry matter per ha. The biomass estimate was converted into carbon equivalent using the ratio of two dry tonnes of biomass to one tonne of carbon (Kurz et al. 2009). Carbon was converted to carbon dioxide equivalent (CO_{2e}) (Kurz et al. 2009). Changes in living and dead biomass stocks over time provide an estimate of net carbon sequestration over the forest stand life.

To capture the potential impacts of butt rot on the quality of logs produced from a stand and hence stand valuation, detailed log grade (quality) schedules were generated using TASS‘s bucking routine (Mitchell 1988). The bucking routine uses a list of inputted prices for various grades of logs (generally larger diameter logs are more valuable than smaller diameter logs) to produce an output file that summarizes the total volume and the breakdown of log grades. Logs are cut to lengths that maximize log value from the merchantable portion of the stem. For the current study, the merchantable portion of the stem was defined using a 12.5 cm diameter lower limit, less tops (10 cm) and stumps (30 cm), while the minimum log length was set to 2.5 m, which is standard for the coastal zone.

Butt rot impacts

Butt rot damage begins at the base of the tree and occupies a greater proportion of the larger diameter portion of the trees. To simulate the impacts of butt rot, an estimate of the decayed portion of the tree at each age was used to truncate the volume of the tree. As the base of the tree is associated with the largest and most valuable logs, this procedure estimates the lost potential value of the tree and stand. WRC is considered disease tolerant to several root diseases; hence, it is considered for root disease management without consideration to butt decay (Morrison et al. 2014). A simulation without decay captures the estimated log volumes and values of the stand without decay, notionally due to removal of the infected stumps of the previous stand before the new stand is established. This procedure is called stumping and involves the removal of roots and the tree root collar (called stump together) using an excavator after the stems are removed (Cruickshank et al. 2018). The efficacy of stump removal on the incidence of butt decay was based on a stump removal trial of 50-year-old planted interior cedar (Cruickshank et al. 2018). It also may be done by push falling where the trees are pushed over with an excavator, which removes the roots, and then the stump part is cut off and the stem harvested.

More specifically, to simulate the expected impact of decay, an estimate of the number of trees and the rate of vertical progression of the decay up the stem of a tree was introduced into the stand simulation at each time step. The proportion of trees with decay and the length and volume of the decay column used in this study is based on work by Buckland (1946), who surveyed cedar butt rot incidence and impact in BC. A polynomial curve was fitted to Buckland’s incidence data for coastal and interior sites from the origin up to age 250 years. The incidence at age 250 was about

80% coast and 100% of interior trees with butt rot. The youngest sites were aged 50 years for the coast and 75 years for the interior. The length of the decay column along the bole was averaged for the different fungi associated with decay being 14% of length on the coast and 29% of length in the interior by age 250 years. Volume loss (in cubic meters) to decay was treated in the same manner as an average loss per tree, being about 4% for the coast and 10% for the interior by age 250 years. The percentage of length and volume losses were linearly interpolated back to the origin from age 250 to construct curves showing both impacts over time. The column of butt decay could then be described as a cone arising from the tree base using these parameters. The incidence of infection and the length and volume enabled butt decay to be modelled over time for each log. The net effect was to reduce the available logs sourced from the lower portion of the trees in the stand. The number of trees with decay and the proportion and volume of high-valued wood lost to decay for each tree and the stand as whole increases with stand age. There are also maybe growth losses caused by the decay fungi and losses to stem breakage, which were not considered.

Deer browse impacts

The impacts of deer browse on stand development and volume were simulated in TASS using a subroutine created specifically for this study. The subroutine consists of two main components. The first component determines the annual probability of browse for each tree based on the tree's location within the stand and the browse level that is to be simulated. Conditional on a tree being browsed, the second component either reduces the growth rate of the tree or kills the tree. The subroutine is initialized through a user-supplied value of deer browse prevalence in the fourth year of growth. In the current context, the term 'prevalence' describes the proportion of trees affected by deer browse within the stand. It is calculated as: [trees per ha browsed/trees per ha planted]. In practice, browse prevalence in the fourth year of growth would be obtained from post-establishment surveys. However, for the purpose of this study, we use the hypothetical value of 85% prevalence, which would be among the more severely affected stands.

The subroutine assumes that in each of the first four years following stand establishment, deer browse a proportion of the previously unbrowsed trees, as well as some of the same trees that were browsed in the previous year. Furthermore, the routine assumes that the probability of annual first browse decreases over time, dropping to zero by age five. We rationalize this decision because terpene levels increase with tree age, thus rendering the foliage less palatable. Mitchell (1964) also noted that browsing by deer was heaviest among trees with a height less than 1.3m and that trees which exceeded this height tended to show negligible signs of browsing. For cedar stands with average site productivity, TASS predicts a top height of approximately 1.44m at stand age four. Thus, it seemed reasonable to assume that damage to the leader caused by deer browse should cease in the fifth year of growth.[4]

When simulating deer browse in TASS, an annual probability of first browse (P_B) is assigned to each tree, in each of the first four years of growth. How we arrived at these probabilities requires some elaboration. As a starting point, we used the data from Russel and Kimball (2010), where three levels of browse prevalence (86%, 64%, and 30%) in a planted cedar stand are reported after four years of growth. Using these values as a guide, we generated annual probabilities of first browse for each tree in a hypothetical test population of 1,000 trees. Under the constraint that browse probabilities decrease with age, we iteratively tested different annual probabilities until they satisfied the requirement of approximating the prevalence values reported by Russel and Kimball (2010). An equation was then formulated in which P_B was a linear function of age and prevalence in the fourth year. The equation allows for P_B to be estimated for any level of browse prevalence. The equation, which was fitted using the data from the hypothetical test population described above, took the following form:

$$\mathrm{P_B} = -0.063 + 0.013 \times \mathrm{age} + 0.813 \times \mathrm{prevalence} - 0.165 \times (\mathrm{prevelance} \times \mathrm{age}) \tag{1}$$

where all terms are already defined.

At the beginning of a simulation, a final adjustment to P_B is made to reflect deer browsing patterns within a cutblock. Specifically, the probability of being browsed decreases with increasing distance from the edge of an intact adjacent stand, which could be simulated in TASS's spatially explicit environment. To account for the chance event that trees are browsed in successive years, the following rules were applied:

1. 75% of trees browsed once will be browsed again in the following year,
2. 50% of trees browsed twice will be browsed again the following year, and
3. 25% of trees browsed three times will be browsed again the following year.

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[4] A longer browse time-frame is required to simulate the impacts of elk given their much larger size and longer browse reach. As mentioned earlier, elk impacts are not considered in this paper as their range on the coast is not as ubiquitous as black-tailed deer.

Although there was no scientific data to support these rules, anecdotal evidence from cedar tree breeders suggested that our values were plausible.

In the deer browse subroutine, browsed trees have their height growth reduced each year until they reach the fifth year. The amount of height growth reduction is determined by a browse damage class assigned to each tree. Once again, we used the data from Russell and Kimball (2010) to determine the proportion of trees that fell into each class. For the current study, in which browse prevalence was 85%, 17% of browsed trees were set to experience light damage, 46% severe damage, and 37% were killed. The height growth was reduced by 70% for trees with severe damage, and by 30% for trees with light damage, which was consistent with findings reported by Cockle and Ettl (2010).

Financial and carbon considerations

Following Bogdanski et al. (2018), we used a discounted cash flow model to evaluate the feasibility of stump removal to control root disease or mitigation of deer browse damage. The discounted cash flow method has long been used to assess forestry investments and treats forests as a capital good (Klemperer 1996; Viitala 2016). We assumed an infinite time planning horizon to allow ready comparison of different scenarios. The method involves summing the flow of expected revenues and costs of management over time and discounting them to a base year. For deer browse and decay, we considered with and without impacts to estimate an upper bound on economical expenditures to mitigate damages. Economic information includes costs of stand establishment (cost of tree times number of trees per ha), timber and carbon prices, and the social discount rate. Formally, the method is captured by equations 2 through 5. In all expressions, rotation age, and thus merchantable harvest or final carbon stocks, is chosen to maximize the net present value from a set of repeated management actions over time. When considering only timber values, $F^{nd}(T)$ and $F^{d}(T)$ represent expected land values — often called the soil expectation value (SEV) or land expectation value (LEV) — where stumping or deer damage mitigation are conducted and not conducted on the stand, Equations 2 and 3, respectively,

$$\max_{T} F^{nd}(T) = \frac{wh_{nd}(T) - e_0^{nd}(1+r)^T}{(1+r)^T - 1} \tag{2}$$

$$\max_{T} F^{d}(T) = \frac{wh_{d}(T) - e_0(1+r)^T}{(1+r)^T - 1} \tag{3}$$

where, w is the real price of timber at the time of harvest, T, $h_{nd}(T)$ and $h_d(T)$ are merchantable wood volume at time of harvest, T, for undamaged, *nd*, and damaged (either due to decay, browsing or both), *d*, stands, e_o is stand establishment costs at stand age of 0, with (*nd*) or without mitigation expenditures such as stumping or caging, and r is the real discount rate. The optimal economic rotation age and harvest volume will differ for each equation and decay/browse impact scenario and will vary with changes in parameters. For simplification, while considering decay impacts, we assumed that there is no initial standing value in the existing diseased stand, i.e., at time zero, we assume harvest revenues are equal to harvest costs. That is, we assumed un-treed land with infected stumps as the starting point of the analysis. With those considerations set aside, for similar economic conditions, stumping is economically feasible if costs of stumping are equal to or less than the difference between an un-diseased or diseased stand. Similarly, deer protection measures are economically feasible if costs are less than or equal to the difference between an un-browsed and a browsed stand. In essence, increased future timber values need to be sufficient to cover the incremental decay or deer browse protection expenditures.

When considering carbon and timber values we followed van Kooten et al. (1995). $G^{nd}(T)$ and $G^{d}(T)$ represent the cases where stands are undamaged and damaged by decay or browsing, Equations 4 and 5, respectively,

$$\max_{T} G^{nd}(T) = \frac{wh_{nd}(T)-e_0^{nd}(1+r)^T}{(1+r)^T-1} + \frac{\sum_0^T \tau(c_t-d_t)(1+r)^{T-t}-\gamma\tau\delta_T}{(1+r)^T-1} \tag{4}$$

$$\max_{T} G^{d}(T) = \frac{wh_{d}(T)-e_0(1+r)^T}{(1+r)^T-1} + \frac{\sum_0^T \tau(c_t-d_t)(1+r)^{T-t}-\gamma\tau\delta_T}{(1+r)^T-1} \tag{5}$$

where τ is the price of carbon, c_t is the quantity of carbon sequestered at age t, d_t is the amount of carbon released from dead organic matter pools at age t, δ_T is the volume of stored live and dead forest carbon at time of harvest, T, and γ is the proportion of this forest carbon stock released to the atmosphere. Note when price of carbon is zero Equations 4 and 5 collapse to Equations 2 and 3, respectively. For simplification, we assumed that there is no standing value in the existing stand. In effect, the value of accumulated sequestered carbon is offset by the cost of releasing the carbon back to the atmosphere at time of harvest, T, and the net present value of all carbon released from the decay of dead organic matter over the life of the forest stand. The proportion of carbon released into the atmosphere at the time of harvest, γ, may be less than 1. Carbon removed from the site in harvested logs may be stored in long-lived forest products (e.g. lumber in buildings) or eventually disposed to landfills. Alternatively, stumps and other harvest residuals may be used offsite for bioenergy or other products. This again might reduce the total amount of emissions. In either case, any assumption of $\gamma<1$ will increase the net present value of carbon benefits and shorten the rotation age (Bogdanski et al. 2018). Given the uncertainty regarding carbon emissions released to the atmosphere, γ, we modelled this parameter as a probabilistic variable, discussed further below. The rate of decay of the dead organic pools was assumed to be 6% per annum and approximates annual rates used in the Carbon Budget Model of the Canadian Forest Service (CBM-CFS3) (Kurz et al. 2009). Like the timber-only scenarios, decay and browse mitigation measures are economically feasible if they are less than or equal to the difference between the undamaged and damaged scenarios.

Stand values and log quality

To better refine the potential impacts of decay or browse on WRC stand values, we explicitly account for changes in the quantity of different grade logs produced from the simulated stand. Recognizing that the value of a tree is derived from the price of final products that the wood will be used for (e.g., boards, planks, furniture, paper gowns) and the costs to transport and transform the tree into those products, we account for different types of logs generated from the simulated stands and price them differentially. Based on log grade conventions used in British Columbia, four types of logs are produced from a stand simulated in TASS: saw logs – minimum top diameter of 38cm and lengths of 8 to 13m; gang logs – minimum top diameter of 20cm and lengths of 8 to 13m; chip-and-saw (or utility) logs minimum top diameter of 12.5cm and lengths of 5.1 to13m; and, pulp logs – minimum top diameter of 12.5cm and length of 5m. The quantity of each log grade depends on the stand's age, site productivity, and stand density (trees per hectare).

Therefore, $wh_{u,d}(T)$, stand value for undamaged, u, and damaged, d, stands (timber price, w, times harvested volume at time of harvest, T), in equations 2 to 5 becomes

$$wh_{u,d}(T) = s \times q_s + g \times q_g + u \times q_u + pxq_p \tag{6}$$

where s,g,u,and p are the prices (C\$/m^3) of saw, gang, chip n'saw (utility), and pulp logs in the standing forest, respectively, and q_s, q_g ,q_u , and q_p are the volumes (m^3) of these different log grades. All prices in Equation 6 are treated as probabilistic variables, as explained below.

Data and assumptions

The analysis involved both deterministic parameters and probabilistic variables. Deterministic parameters include: stand planting costs; discount rate; carbon prices; and pulp price (Table 1). All prices and costs are in Canadian dollars (C$). The stand planting cost is composed of an expected planted seedling cost of C$1 per tree times the number of trees planted, which was either 800 or 1000 per hectare. A range of real discount rates was considered between 2% to 8%. The lower range of values (2-4%) aligns with estimates of 2.5-3.5% for long-lived investments on public lands in Canada (Boardman et al. 2010). The higher range of values (5-8%) aligns more with the discount rates expected to be held by private interests in forestland, which is particularly relevant on the coast of BC where there is considerable private forest land. Pulp log prices are typically priced at a fixed administrative price of C$0.25/m^3 in British Columbia and so we assumed this value in our calculations.

Table 1. Deterministic (static) parameter definitions and values.

Deterministic Parameter	Base value	Alternative values
e — stand planting costs (seedling cost times seedlings per hectare)		
Seedling cost (C$/tree)	1.0	Not considered
Seedlings per hectare	800	1000
τ — carbon prices (C$ per tonne of CO_2)	50	0,20,80
r — discount rate (%)	4	2,3,5,6,7,8
p — pulp log price (C$/m^3)	0.25	not applicable

We considered timber prices at time of harvest to be probabilistic to capture the inter-annual variation of prices and to capture sub-regional variation due to differences in harvesting conditions and distance to markets. Inclusion of a probabilistic treatment of timber prices results in a probability distribution function of the estimated SEVs, which permits an assessment of the probability of breaking-even on a known mitigation action and comparing this to acceptable risk tolerance levels. The inflation-adjusted annual average timber price sold by auction for years 2006 to 2020 were used to model prices. The data was retrieved from the BC Government's timber billing database.[5] As the reported timber values are a blend of different log grades, differentiated

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[5] Refer to: https://a100.gov.bc.ca/pub/hbs/ (accessed on January 30, 2021).

log prices were estimated using market log information published by the Government of BC.[6] Assuming that the standing timber log grades correspond one-to-one to the market value of traded logs, standing saw log price premiums were estimated by using the market differences between log grades and the average proportion of log grades harvested annually from coastal stands. The exact estimation procedure of the log grade price breakdown is outlined in Appendix 1. The estimated saw log prices were fitted to a PERT distribution using Palisades @Risk software version 8.1. Other distributions were also considered, but the PERT distribution (a form of the beta distribution) resulted in the best fit based on the Akaike information criterion (AIC), Bayesian information criterion (BIC), average log-likelihood test, and Chi-squared statistic. The parameter values for the minimum, most likely, and maximum values of the PERT distribution are shown in Table 2. Due to insufficient data on the value of gang and chip-and-saw logs at the stand level, log market data from the coastal log market was used to determine potential price discounts relative to saw logs for these other log grades. A high, low, and average discount were calculated using available market data from 2013 to 2020. These three values were used to model the price discount as a probabilistic variable drawn from a PERT distribution (Table 2). The non-saw log prices, other than pulp, were calculated for each iteration of the Monte Carlo simulations by multiplication of the saw log price and the respective price discount. Figure 1 shows the simulated right-skewed distributions of saw, gang, and chip-and-saw timber prices and the differences in their respective distributions. The mean, 10th percentile and 90th percentile values for the three price distributions are summarized in Table 3.

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[6] Refer to: https://www2.gov.bc.ca/gov/content/industry/forestry/competitive-forest-industry/timber-pricing/coast-timber-pricing/coast-log-market-reports

Table 2. Stochastic variable definitions, distributions and parameters.

Parameters	Description	Distribution	Distribution values
s	saw log price (C\$/m^3)	PERT[a]	min, most likely, max={38.26, 38.26, 243.82)
ρ_g	gang log price as proportion of saw log price; multiplied by s to calculate gang price, g (C\$/m^3)	PERT	min, most likely, max={0.63,0.75,0.80}
ρ_u	Chip-and-saw log prices as proportion of saw log price; multiplied by s to calculate chip-and-saw price, u (C\$/m^3)	PERT	min, most likely, max={0.35,0.44,0.56}
γ	proportion of forest carbon stocks released to atmosphere at time of harvest	Triangular	min, most likely, max={0.50, 0.75, 1.00}

Note: [a] *PERT stands for Program Evaluation and Review technique and is a special form of the beta distribution.*

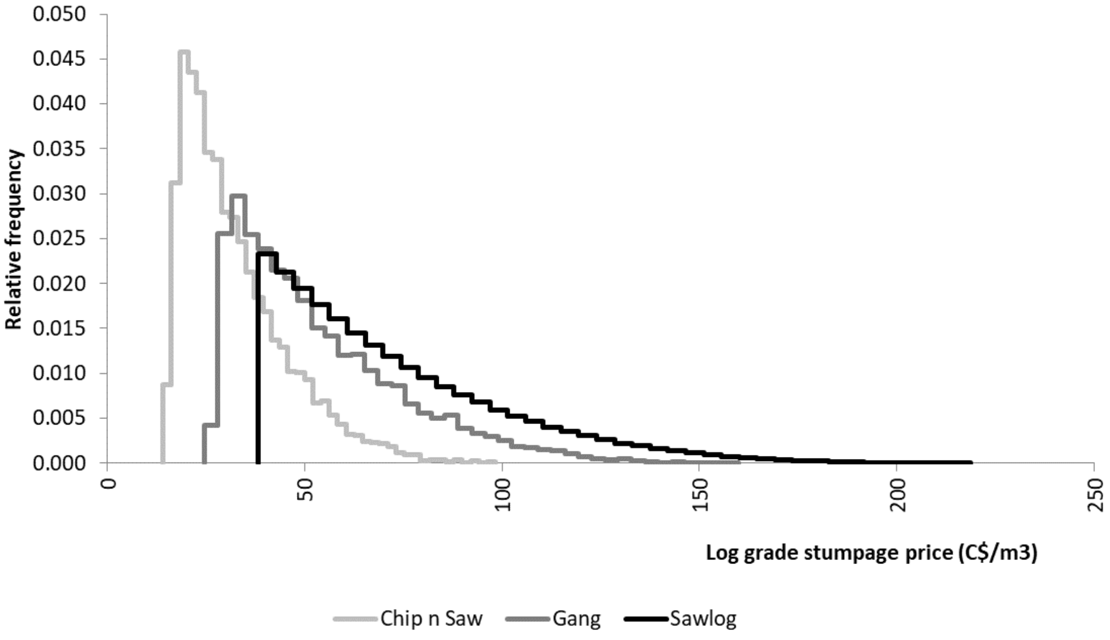

Figure 1. Simulated timber stumpage price distributions for saw, gang, and chip-and-saw logs, n=10 000.

Table 3. Mean, 10th percentile and 90th percentile of simulated saw, gang, and chip-and-saw log price distributions.

Distribution	Mean	10%	90%
Saw	C$72.52	C$42.54	C$114.10
Gang	C$53.54	C$31.40	C$84.68
Chip-and-saw	C$32.28	C$18.70	C$51.07

There is currently a considerable range of global carbon dioxide prices (taxes) (Kossoy et al. 2015). However, as of 2022, BC has a carbon tax of C$50/t CO_{2e} levied on fossil fuels consumed and is expected to increase over the coming years[7]. As there is no general payment/levy for carbon sequestered or released from managed public forests in BC, though a few private biological sequestration projects occurred under BC's offset program[8], it is unclear what an effective carbon price might be for forest carbon sequestration or an equivalent shadow price used by public land managers to guide investment decisions. Due to this uncertainty, we consider four possible carbon prices, C$0, C$20, C$50, and C$80 per tonne of CO_2. All things constant, a higher carbon price will increase the optimal harvest age and increase the soil expectation value (Bogdanski et al. 2018).

As explained above, it is unclear what proportion of carbon will be released after or at the time of harvest. So given the uncertainty, we treat this parameter as a random variable drawn from a triangular distribution with a minimum value of 0.5, a maximum value of 1.0, and a mid-value of 0.75 (see Table 2). A lower proportion reduces the cost of releasing carbon at the time of harvest and effectively lowers the optimal harvesting age, and increases the soil expectation value (Bogdanski et al. 2018).

Finally, we do not explicitly model increased management costs to mitigate the impacts of decay nor deer browsing, with one exception. This is because mitigation measures vary considerably in costs and effectiveness, though stump removal is better understood than deer browse protection measures with estimated efficacy of around 90 percent (Cruickshank et al. 2018). Instead of explicitly accounting for mitigation costs, we compare with and without present value damage scenarios to estimate an upper threshold on potential mitigation expenditures. As most of the mitigation costs considered for decay and deer browse mitigation occur at the beginning of the

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[7] Refer to: https://www2.gov.bc.ca/gov/content/environment/climate-change/clean-economy/carbon-tax?keyword=carbon&keyword=price

[8] Refer to: http://www2.gov.bc.ca/gov/content/environment/climate-change/industry/selling-offsets

planning horizon, they are approximately present value costs and can readily be compared to present value avoided damage calculations. Although, it is important to recognize omission of the exact value does affect the calculated optimal rotation ages and SEVs for with-treatment scenarios and thus the simple subtraction of these costs from the net change in SEVs between with and without scenarios are an approximation. However, given the large number of conceivable permutations of cost scenarios and effectiveness, the approach adopted in this study produces a broad set of results for comparison to draw robust conclusions.

The one measure we explicitly model is planting more seedlings per hectare to mitigate potential decay and deer damages. Given the assumed value of one dollar per seedling, this measure amounts to an increased establishment cost of C$200/ha as planting density increases from 800 to 1000 stems per ha. This measure is considered as tree mortality and growth loss from deer browse is believed to more likely occur in the first year of browsing and thus planting more seedlings will partially compensate for losses. Also, as decay losses tend to occur in later years, we hypothesize that increased planting density might lead to greater production of more valuable logs.

The calculated expenditure thresholds can be compared to possible mitigation expenditures while accounting for effectiveness. Table 4 summarizes information collected on the cost and effectiveness of different mitigation measures. For example, Bogdanski et al. (2018) find stumping costs in the interior of BC to range from C$700 and C$1,100 per hectare (2012 base year). Based on previous studies, the effectiveness of stumping on reducing root disease is considered high (Morrison et al. 2014). Stump removal to control butt rot is a new control concept that appears to be similar to root disease control in efficacy (Cruickshank et al. 2018). With regard to deer damage mitigation, the options are more numerous than that of decay, as are the known levels of effectiveness. Options include higher planting densities, which we consider, planting deer-resistant WRC seedlings, using cones, wire cages, mesh covers, tubing, fencing, or introducing chemical repellants onto the plantation (Booth and Henigman 1996). The cost of each measure varies considerably and depends on planting densities and site location (e.g. remoteness). Deer browse-resistant seedlings and chemical repellants have lower estimated costs (C$200 to C$400/ha), but their effectiveness is very unclear. Cost estimates for coning, tubing, netting and caging an entire hectare of plantation are highly variable (C$3,000 to C$12,200/ha) (Henigman and Martinz 2002, Booth and Henigman 1996) but are expected to be fairly effective (Henigman and Martinz 1996).

Table 4. Rough estimates of costs of mitigation measures and effectiveness (all values in 2020 Canadian dollars).

Practice	Mitigation Objective	Low cost	High cost	Efficacy
Stumping	Butt rot	C$780/ha	C$1120/ha	High
Increased planting density	Butt rot/deer browse	C$0.9/tree	C$1.1/tree	Low - Moderate
Browse resistant seedlings	Deer browse	C$0.3/tree	C$0.4/tree	Low to Moderate
Caging	Deer browse	C$4 500/ha	C$11 800/ha	Moderate - High
Mesh netting	Deer browse	C$3 650/ha	C$4 250/ha	Moderate
Coning	Deer browse	C$3 000/ha	C$12 200/ha	Moderate - High
Tubing	Deer browse	C$4 200/ha	C$8 000/ha	Moderate- High
Chemical repellants	Deer browse	C$400/ha	Unknown	Unknown
Fencing	Deer browse	C$15 800/ha		High

Microsoft Excel and Palisades @Risk software (ver.8.1) were used to perform all calculations and Monte Carlo simulations involving Equations 2 to 5. All Monte Carlo simulations involved the Latin Hypercube sampling method using the Mersenne Twister random seed generator to generate 10,000 iterations for each simulation. In total, 672 combinations of carbon price, discount rate, stand density, site index, and damage type were modelled.

RESULTS

Merchantable volume and carbon gains – butt rot control

Figures 2 and 3 show the merchantable volume for diseased and non-diseased stands and the specific log volume gains, respectively, from removing butt rot losses across all site types. For high site indices (SIs) of 30 and 35, there is no significant difference in stand volume until after age 40. Similar results were obtained for stand age 50 and site indices 20 and 25. Significant volume gains do not occur until after 75 years across all site indices, with approximately 75% of the volume gains achieved after this age (Figure 2). The bulk of the volume gains are in the form of gang logs for SI 20, a mix of gang and saw logs for SI 25, and mainly saw logs for SI 30 and 35 (Figure 3).

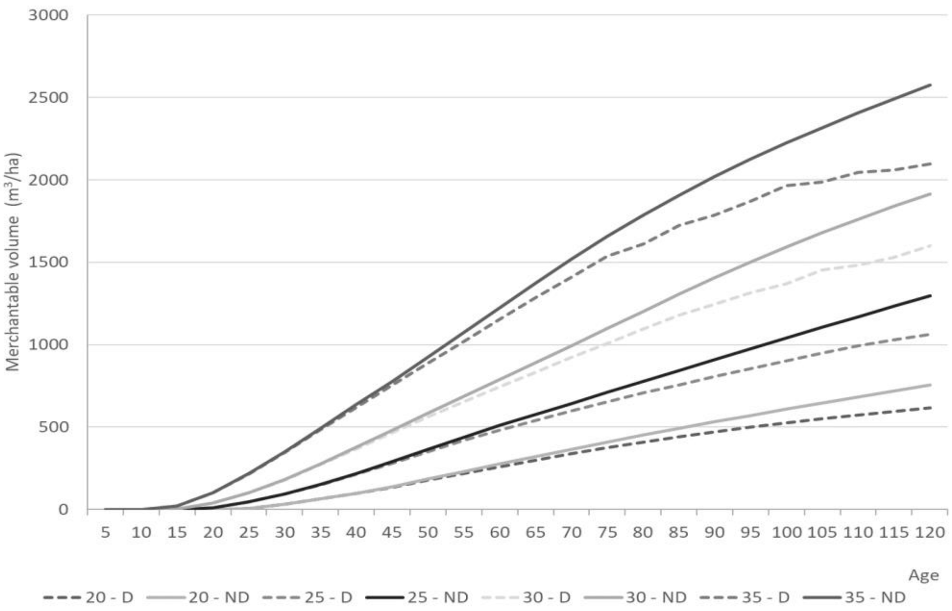

Figure 2. Merchantable stand volume for decay (D) and non-decay (ND) stands of site indices 20, 25, 30, and 35. No deer browse impacts and initial stand density of 800 stems per hectare.

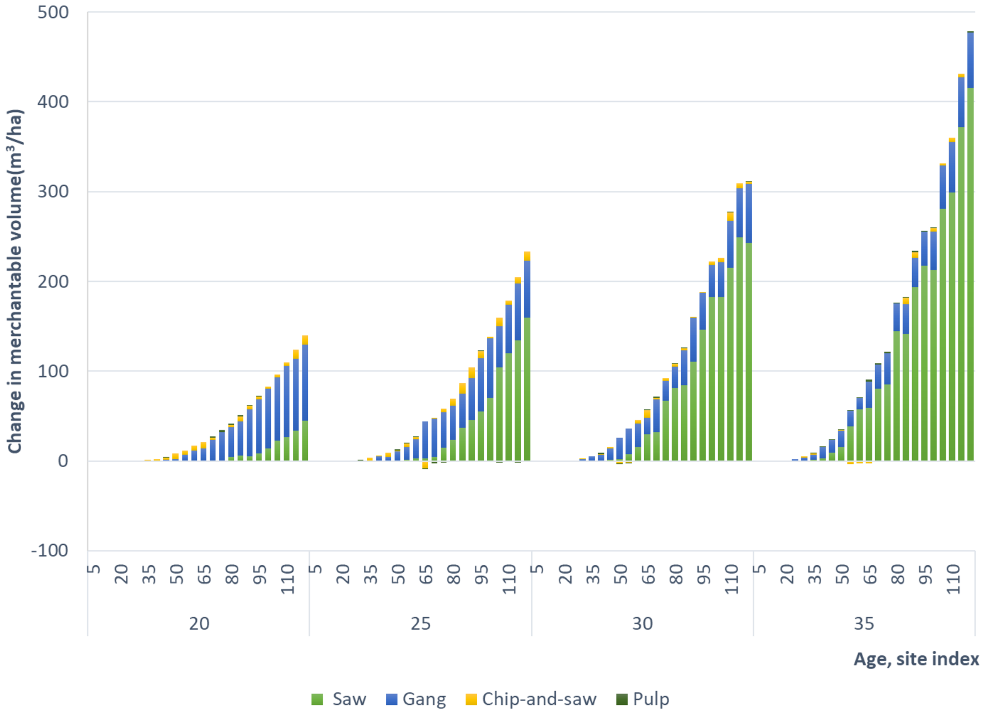

Figure 3. Change in quantity of merchantable log types due to removal of butt rot for different site indices. No deer browse impacts and initial stand density of 800 stems per hectare.

Merchantable volume and carbon gains – deer browse control

The volume projections for browsed and un-browsed stands and the change in log volumes are illustrated in Figures 4 to 6. Because deer browse occurs early in stand development, the impacts at rotation are less severe compared to the diseased scenario (compare Figure 2 and Figure 3). Initially, the gains in merchantable volume obtained by eliminating deer browse are greatest on the more productive stands. However, after 70 years, the gains in merchantable volume remain similar across all sites (Figure 5). The change in the quantity of the different log grades is very different from the effects of decay, and the amount of impact is lower (compare Figure 3 to Figure 6). There is a shift from saw logs towards other log types, such as gang, across all site indices and occurs more rapidly for higher than the lower quality sites.

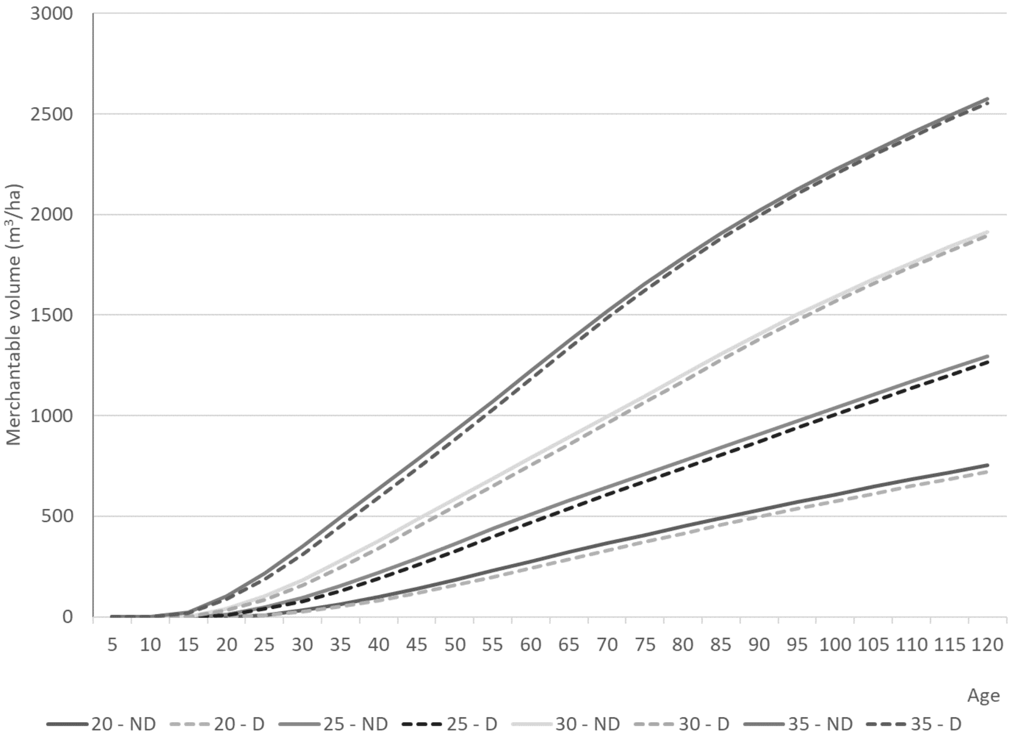

Figure 4. Merchantable stand volume with deer-browse damaged (D) and non-damaged (ND) stands for site indices 20, 25, 30, and 35. No root or butt rot on site and initial planting density is 800 stems per hectare.

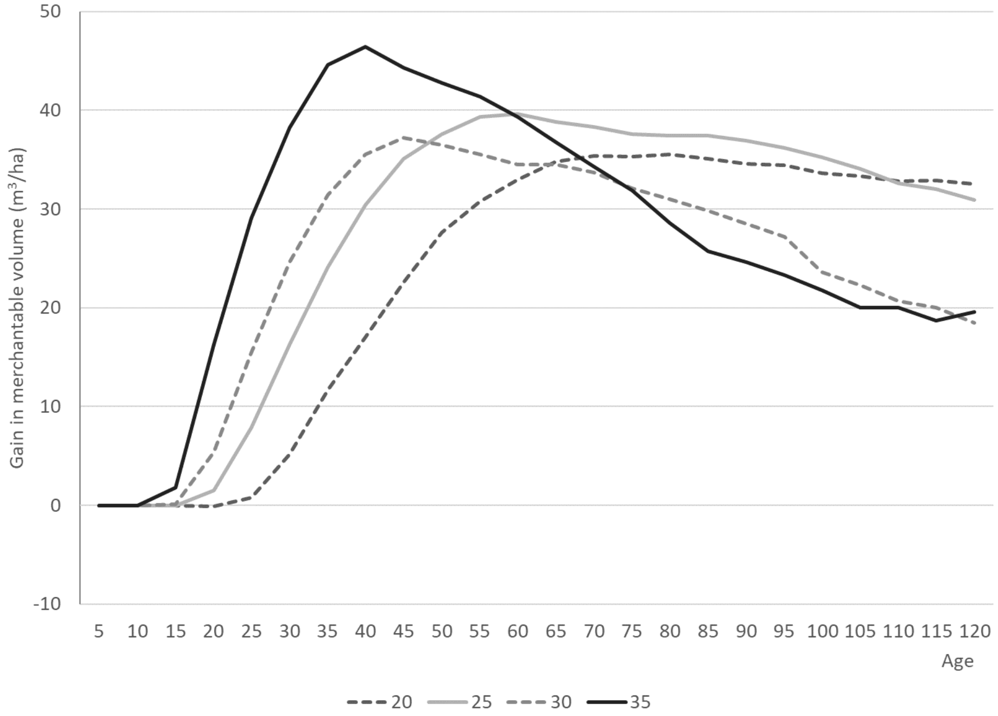

Figure 5. Gain in merchantable volume from eliminating deer browse, all site indices, initial planting density of 800 stems per hectare, and no butt rot.

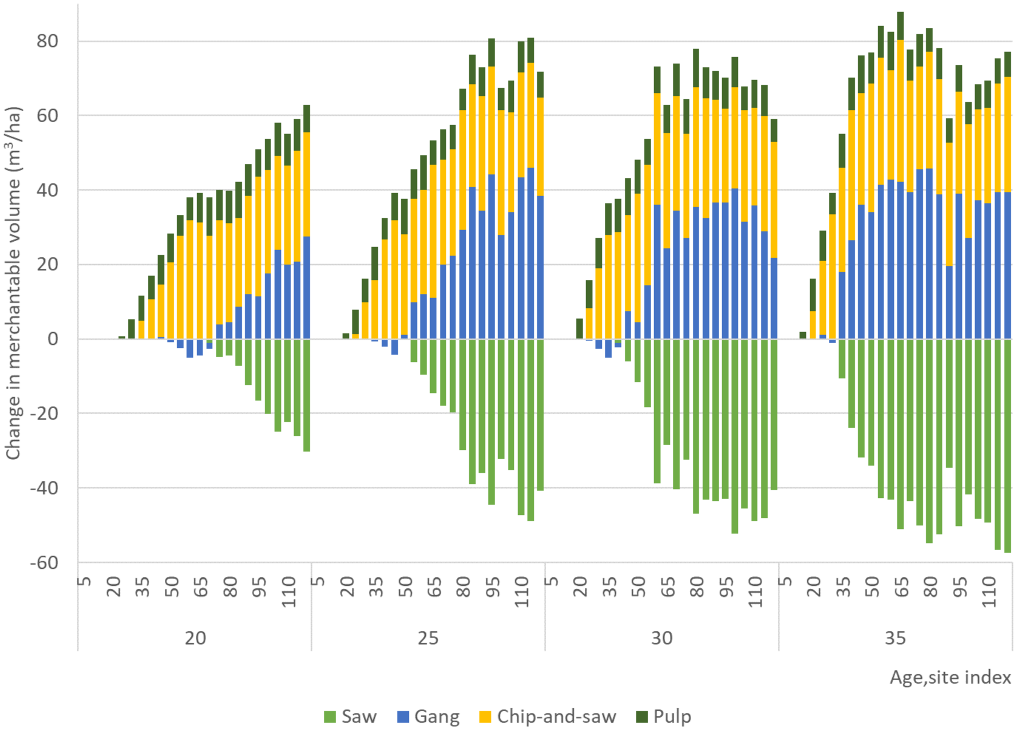

Figure 6. Change in quantity of log types due to elimination of deer browse for all site indices, initial stand density of 800 stems per hectare, and no butt rot.

A higher planting density of 1,000 stems per ha has mixed results in mitigating the combined impact of deer browse and decay (Figure 7). On stands of SI 20 and 25, volume gains occur slowly over the first few decades before plateauing over the subsequent stand ages. On stands of SI 30 and 35, volume gains occur more rapidly over the first few decades, but the gains become highly variable beyond age 60, with negative gains on SI 35 at ages 90 and 120 and only small gains at age 105 on SI 30. The shift to higher density (Figure 8) leads to an increase in lower quality logs across all site indices, though net losses of saw logs are not as large as those with complete elimination of deer browse (compare with Figure 6).

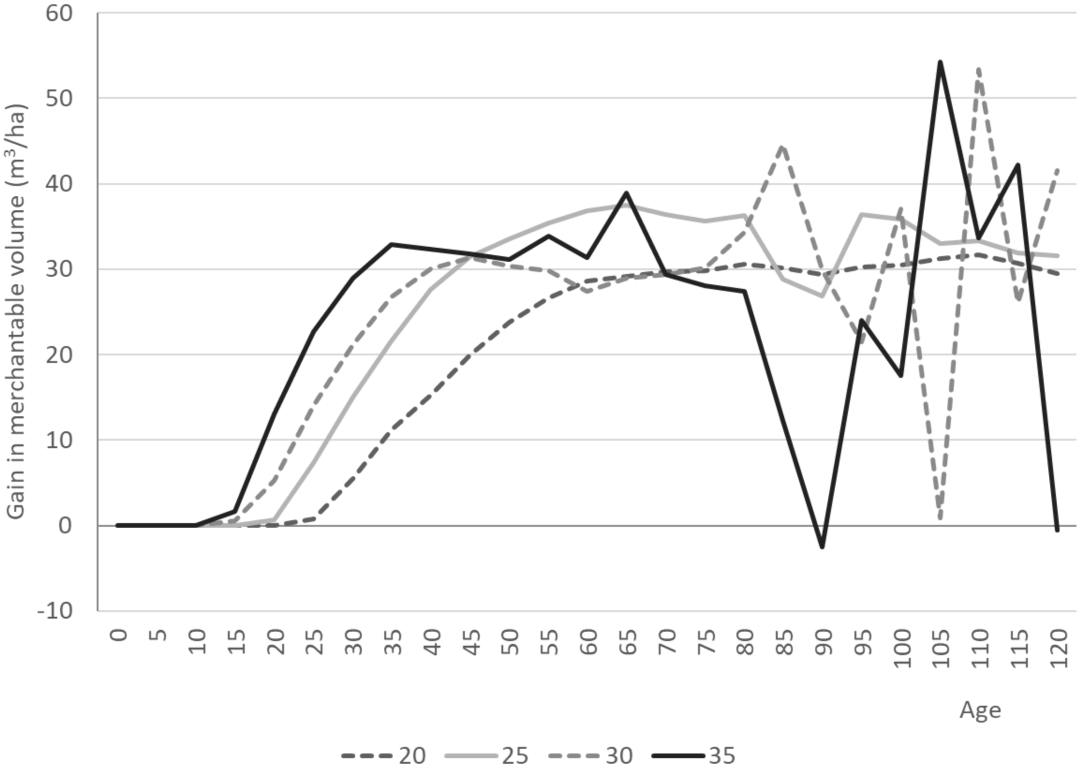

Figure 7. Gain in merchantable volume per hectare by increasing initial stand density from 800 stems to 1000 stems per hectare on stands with butt rot and deer browse damage for all site indices.

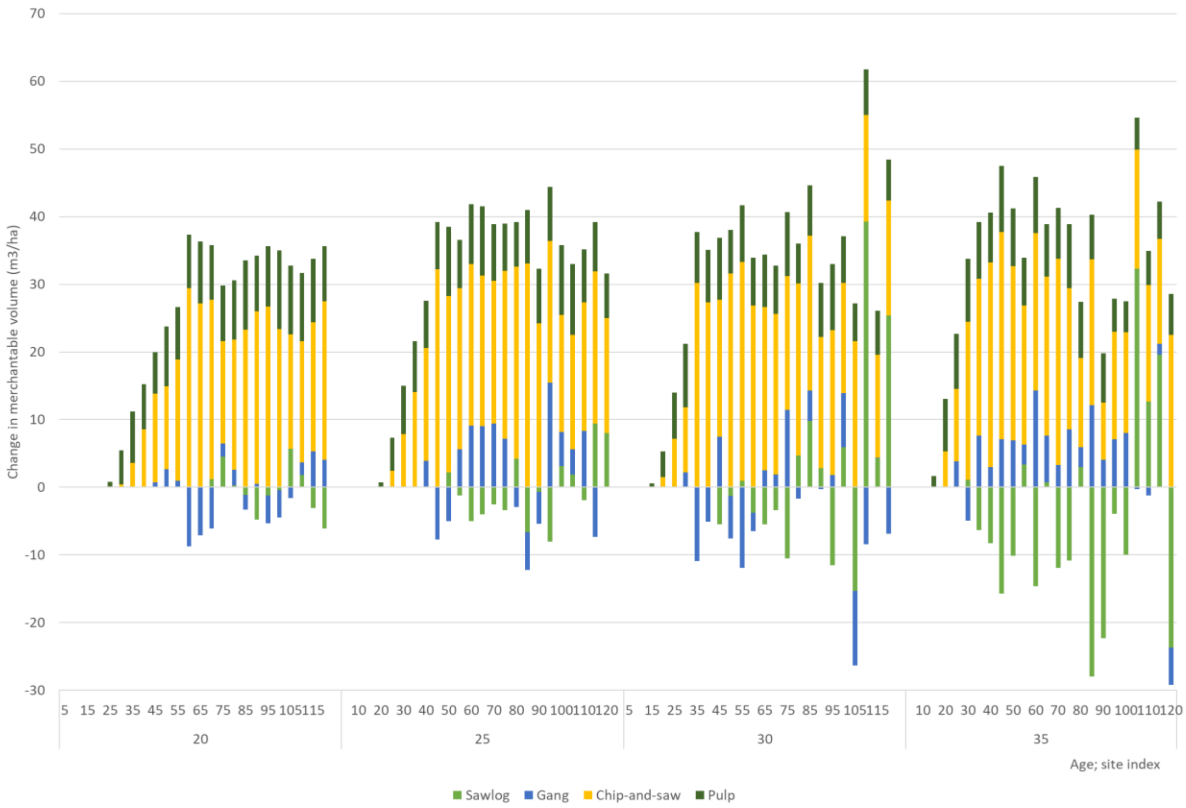

Figure 8. Change in quantity of log types due to increased planting density from 800 stems to 1000 stems per hectare in the presence of deer browse and butt rot.

Optimal economic rotation

The minimum, maximum and mode of the simulated distributions of the optimal rotation age that maximizes the soil expectation values (Equations 2 to 5) are reported for the different damage scenarios, carbon prices, site indices, and selected discount rates in Table 5. The mode statistics represent the most likely rotation age given the log prices and proportion of carbon not released to the atmosphere after harvest. The rotation ages decrease with higher site indices, increasing discount rate, and higher timber prices, and increase with higher carbon prices. Expected optimal rotation is often lower on sites with decay than with deer damage or without damage. Under many scenarios, the inclusion of carbon prices leads to a maximum rotation age of 120 years. This occurs more often on lower site indices, low discount rates scenarios, or higher carbon price scenarios. Furthermore, though not shown, higher optimal rotation ages are associated with low log prices and high proportions of carbon released at harvest. This is consistent with the results of Bogdanski et al. (2018).

Table 5. Minimum, mode, and maximum statistics for optimal rotation distributions from simulation runs across different carbon prices, site indices, and damage scenarios for selected discount rates. The base case scenario involves no disease and no deer damage. Deer scenario involves deer damage only. Disease scenario involves only butt rot. Stand density 800 stems per hectare.

				2%			**5%**			**8%**	
Carbon Price	**Site**	**Scenario**	**Min**	**Mode**	**Max**	**Min**	**Mode**	**Max**	**Min**	**Mode**	**Max**
$0	**20**	Base Case	75	80	85	60	60	60	50	55	60
		Deer	80	85	90	60	60	65	50	55	60
		Decay	70	75	85	55	60	65	50	55	55
	25	Base Case	70	75	75	45	50	55	45	45	45
		Deer	70	75	85	50	50	55	45	45	45
		Decay	70	70	75	45	50	50	40	45	45
	30	Base Case	75	75	75	45	45	50	35	40	40
		Deer	75	75	80	45	50	50	35	40	40
		Decay	65	70	75	45	45	50	35	40	40
	35	Base Case	60	65	70	40	40	45	30	35	35
		Deer	65	65	70	40	45	45	35	35	35
		Decay	60	65	65	40	40	45	30	35	35
$20	**20**	Base Case	85	95	120	60	65	120	55	60	110
		Deer	85	95	120	60	70	115	55	60	105
		Decay	75	85	120	60	65	120	55	60	120
	25	Base Case	75	100	120	50	60	95	45	50	85
		Deer	80	95	115	55	65	95	45	50	85
		Decay	70	80	115	50	60	100	45	50	90
	30	Base Case	75	85	95	50	55	80	40	45	75
		Deer	75	85	100	50	55	80	40	50	70
		Decay	70	85	90	50	55	85	40	45	75
	35	Base Case	65	70	80	45	50	70	35	40	60
		Deer	65	70	80	45	55	65	35	45	60
		Decay	65	70	75	45	50	70	35	40	60
$50	**20**	Base Case	95	120	120	65	120	120	60	120	120
		Deer	95	120	120	65	120	120	60	120	120
		Decay	85	120	120	65	120	120	60	120	120
	25	Base Case	85	120	120	60	120	120	50	120	120
		Deer	85	120	120	60	120	120	50	120	120
		Decay	80	120	120	60	120	120	50	120	120
	30	Base Case	80	120	120	55	75	120	45	120	120
		Deer	80	100	120	55	120	120	45	120	120
		Decay	75	85	120	55	120	120	45	120	120
	35	Base Case	70	75	120	50	60	120	40	60	120
		Deer	70	75	120	50	60	120	40	60	120
		Decay	70	75	120	45	75	120	40	120	120
$80	**20**	Base Case	100	120	120	75	120	120	65	120	120
		Deer	105	120	120	75	120	120	65	120	120
		Decay	95	120	120	75	120	120	65	120	120
	25	Base Case	95	120	120	65	120	120	55	120	120
		Deer	95	120	120	65	120	120	60	120	120
		Decay	85	120	120	65	120	120	55	120	120
	30	Base Case	85	120	120	60	120	120	50	120	120
		Deer	85	120	120	60	120	120	50	120	120
		Decay	85	120	120	55	120	120	50	120	120
	35	Base Case	70	120	120	55	120	120	45	120	120
		Deer	70	120	120	55	120	120	45	120	120
		Decay	70	100	120	50	120	120	45	120	120

Economic analysis

Before assessing the potential to mitigate butt decay and deer browsing, we evaluated the economic feasibility of planting western redcedar on stands without butt disease and deer browse damage.[9] Generally, we found planting western redcedar is economically feasible under most site and economic conditions, with a few exceptions. Soil expectation values of planted WRC stands with and without combined deer and decay damage for stand density of 800 stems per hectare by site index, carbon price, and discount rate were simulated and summarized in Figures A1 and A2 in Appendix 2.[10] The expected mean SEV increases with increasing site index and carbon price and decreases with increasing discount rate and damage. Variation in simulated SEV is greater with site index but decreases with discount rates. Log price variation, especially gang logs, largely account for variation in SEVs shown in Figures A1 and A2. Variation in the proportion of carbon released after harvest causes some variation in the SEV but much less of an impact on overall variation than log prices.[11]

Table 6 summarizes the conditions that do not support financial investment in WRC plantations for mean and 25th and 75th percentile values of the simulated distributions of the SEV. When considering expected mean values, undamaged stands of SI20 are not likely to generate positive SEVs when discount rates exceed 4% and carbon prices are zero. This falls to 3% when SEVs at the 25th percentile are considered. Only SI35 supports plantations under all assumed discount rates in the absence of carbon values. A C$20 carbon price increases the SEV such that planting is financially supported at discount rates as high as 6%. For a carbon price of C$20/t$CO_2$, plantations are economical on all sites greater than SI20 for all discount rate scenarios, except where the initial stand density is 1,000 stems per ha and under highest level of assumed damages.

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[9] We did not consider natural regeneration of WRC, as pure stands of naturally established WRC are not very common.

[10] Results for 1000 stem per hectare are not reported but, under same conditions, mean SEVs are lower under higher stand density scenarios.

[11] Contribution to SEV variation by changes in different log prices and carbon retention are not shown but available upon request. Generally gang logs contribute the most to variation in SEV across site indices, decay conditions and discount rates; although, the proportion of carbon released at harvest becomes relatively more important factor for higher carbon prices and lower discount rates, all else equal.

Table 6. Maximum discount rates and minimum carbon price combinations resulting in mean, 25th and 75th percentile SEV≥0 for different site indices, combined butt decay and deer damage scenarios and planting densities.

	Density (stems/ha)	Site index	Discount rate			Carbon price
			25%	Mean	75%	
No damages	800	20	3%	4%	4%	C$0
(Equations 2 and 4)		20	6%	6%	6%	C$20
		25	5%	5%	6%	C$0
		30	6%	7%	8%	C$0
	1000	20	3%	3%	4%	C$0
		20	5%	6%	6%	C$20
		25	4%	5%	5%	C$0
		30	6%	7%	8%	C$0
Deer and root rot damages	800	20	3%	4%	4%	C$0
(Equations 3 and 5)		20	5%	5%	6%	C$20
		25	4%	5%	6%	C$0
		30	6%	7%	7%	C$0
	1000	20	3%	3%	4%	C$0
		20	5%	5%	5%	C$20
		25	4%	5%	5%	C$0
		25	7%	7%	7%	C$20
		30	5%	6%	7%	C$0

Stumping to control butt rot

Table 7 summarizes the average expected gain in SEV on stands without and with butt rot for different assumed carbon prices and discount rates across site indices. Only scenarios with gains greater than C$700/ha, an assumed lower bound of the cost estimate to stump (refer to Table 4), are reported. Figure 9 shows the 25th to 75th percentiles of the SEV gains between non-decay and decayed stands for each simulation combination of site index, discount rate, and carbon price. Again only scenarios with SEV gains of greater than C$700 at the 75th percentile are reported. Considering the estimated simulation mean values for timber only (Equations 2 and 3), the gains in SEV from removing decay ranged considerably by site index and discount rate. A low discount rate of 2% and an assumed value of C$900/ha for stumping, the mid-range cost estimate for this practice (Table 4), is feasible on sites of SI25 or greater. A slight increase in the discount rate to 3% reduces SEVs such that stumping is likely not feasible, even on sites of SI35. Even considering a positive outlook on the range of possible future WRC timber prices (Figure 9), the economics of stumping is generally poor with discount rates greater than 2%. Considering the 75th percentile of the simulated SEVs, stumping might be supported on SI35 sites under discount rates as great as 3%, if cost is sufficiently low enough and such risk is acceptable (Table 7). If a more risk-averse position is taken then, considering the 25th percentile, stumping is not supported on SI25 even with a 2% discount rate.

The inclusion of positive carbon values (Equations 4 and 5) increased the mean SEV gain (Table 7) from stumping and pushed the range of values upward (Figure 9). For a 2% discount rate and a carbon price of C$20/t$CO_2$, the mean SEV gain increased by approximately C$200/ha to C$250/ha for SI20 and SI35, respectively. These incremental gains quickly diminish as the discount rate increases, from C$741/ha and C$2,447/ha to C$100/ha and C$468/ha due increase from 2% to 4% for SI 20 and 35, respectively. Increasing the carbon price to C$50 or C$80/tCO_2 increases the SEV gain from stumping, as expected, but not substantially for discount rates greater than 3% (not shown). For example, for a 4% discount rate the incremental SEV gain increases approximately C$25/ha and C$75/ha when the carbon price is quadrupled from C$20/t$CO_2$ to C$80/t$CO_2$, for SI 20 and 35, respectively. Considering only the mean increase in SEV from stumping, the number of scenarios that exceed the expected cost of stumping (C$900/ha) only increase by one (SI20 at 2%) when carbon prices increase to C$50/t$CO_2$ and one additional scenario (SI30 at 3%) when carbon price increase to C$80/t$CO_2$. Even an optimistic view of future timber prices and carbon release at harvest time (<100%) does not change the overall results. Using values greater than the 75th percentile only changes the feasible scenarios by one, SI30 with a carbon price of C$50/t$CO_2$ and a discount rate of 3%; however, this assumes this level of risk is acceptable. Taking a more conservative risk position using the 25th percentile as the threshold then, the number of feasible scenarios decrease by six.

Table 7. Mean difference in SEV between stumped and un-stumped stands accounting for timber values and carbon prices (τ) of C$0, C$20, C$50, and C$80/tCO2 by site index and discount rates (r). Only values greater than C$700 shown.

	τ = C$0		τ = C$20		τ=C$50		τ=C$80	
Site Index	2%	3%	2%	3%	2%	3%	2%	3%
20			C$741		C$947		C$1,058	
25	C$920		C$1,254		C$1,693		C$1,916	
30	C$1,630		C$1,939		C$2,364	C$842	C$2,671	C$915
35	C$2,195	C$813	C$2,447	C$1,019	C$2,784	C$1,133	C$3,423	C$1,282

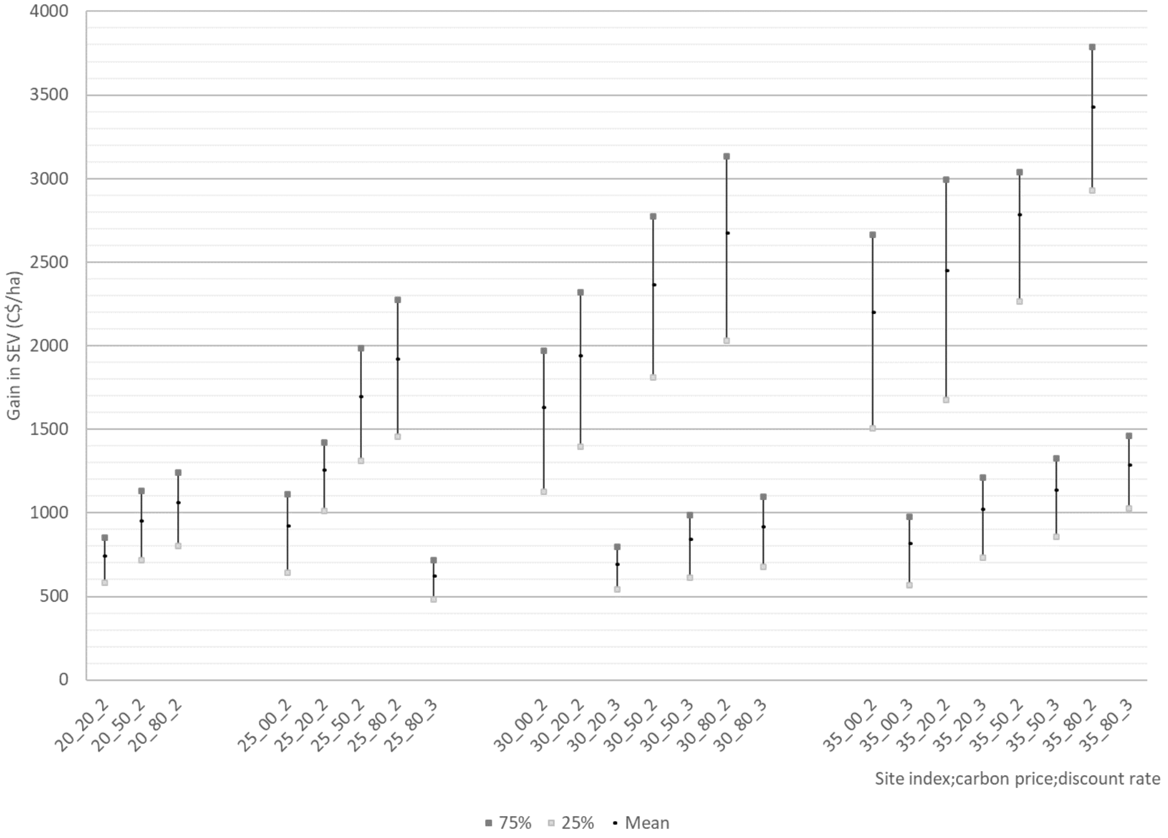

Figure 9. Gain in SEV by removing butt rot impacts by site indices, carbon price and discount rate. Stand density 800 stems per hectare. Only scenarios with SEV greater than C$700 at the 75th percentile reported.

Reduction of deer browsing damages

Table 8 summarizes the average gain in SEV on stands without and with deer damage for different assumed carbon prices and discount rates across site indices. Only scenarios with a SEV greater than C$200/ha are reported, the low cost bound for deer browse protection measures (deer resistant seedlings reported in Table 4). While Figure 10 shows the 25th to 75th percentile ranges of SEV gains between un-damaged and damaged stands for each simulation combination of site index, discount rate, and carbon price. Only scenarios with SEVs greater than C$200/ha reported.

Assuming that defensive measures are at least C$200/ha, deer management is not feasible under any scenario when carbon prices are zero (Equations 2 and 3). However, under a carbon price of C$20/t$CO_2$, deer management is feasible on stands of SI20 if discount rates are less than 5%.

The set of feasible deer management scenarios increases as carbon prices increase. For example, when carbon prices are C$50/t$CO_2$, expenditures of C$200 per hectare are supported on all site indices with the exception of a discount rate of 8% on SI20. As can be seen in Table 8, deer management expenditures greater than C$200 may be supported under several combinations of discount rates and carbon prices, especially carbon prices of C$50/t$CO_2$ and C$80/t$CO_2$.

Higher expected log prices on SEVs have little impact on the results, except on stands of SI35. However, when log prices are expected to be higher, expenditures on deer damage might increase by C$200 under a 2% discount rate and high carbon price scenarios (C$50 and C$80).

Table 8. Mean difference in SEV between deer damaged and un-damaged stands accounting for timber values only, by site index and discount rates. . Only scenarios with mean SEV greater than C$200 reported.

	Discount rate (*r*)						
	2%	3%	4%	5%	6%	7%	8%
	τ = C$20						
20	C$446	C$327	C$236				
25	C$514	C$426	C$327	C$255	C$201		
30	C$401	C$385	C$333	C$277	C$228		
35	C$822	C$558	C$445	C$376	C$316	C$270	C$230
	τ=C$50						
20	C$993	C$724	C$538	C$406	C$311	C$242	
25	C$1,197	C$941	C$740	C$584	C$464	C$373	C$303
30	C$1,103	C$954	C$799	C$661	C$546	C$453	C$377
35	C$1,569	C$1,263	C$1,045	C$875	C$738	C$624	C$529
	τ=C$80						
20	C$1,571	C$1,150	C$858	C$648	C$497	C$387	C$306
25	C$1,910	C$1,499	C$1,180	C$932	C$742	C$597	C$485
30	C$1,766	C$1,534	C$1,285	C$1,063	C$878	C$727	C$605
35	C$2,165	C$1,885	C$1,623	C$1,384	C$1,175	C$997	C$847

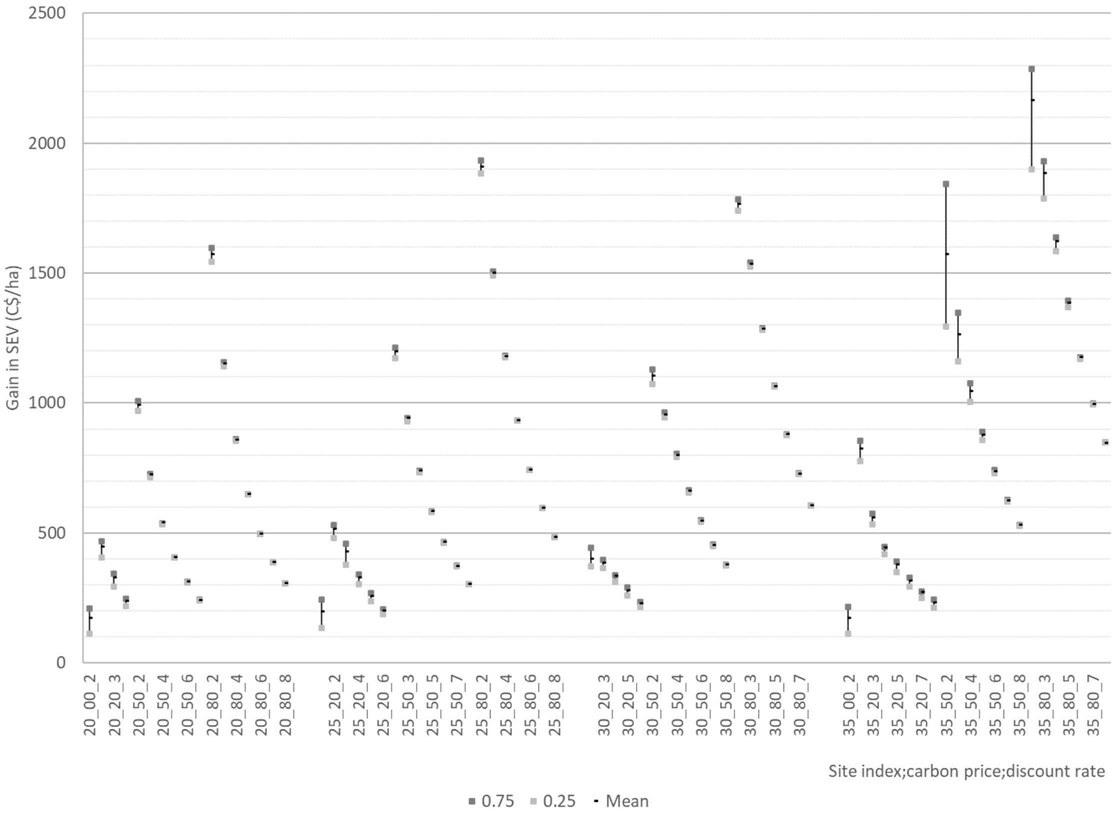

Figure 10. Gain in SEV from removing deer predation from stand by site index, carbon price and discount rate. Stand density 800 stems per hectare. Only scenarios with potential SEV gain greater than C$200 at 75th percentile reported.

Increased planting density to mitigate possible impacts of deer browse or decay

Table 9 summarizes the average gain in SEV on stands by planting 1,000 stems per hectare rather than 800 stems per hectare to mitigate deer and decay damages for different assumed carbon prices and discount rates across site indices. Figure 11 shows the mean and 25th to 75th percentile range in SEV gains between the high density and base density stands for combinations of site index, discount rate, and carbon price.

Considering timber-only scenarios (Equations 2 and 3), only three scenarios support a higher planting density. This occurs on SI25 with 2% discount rate and SI35 with discount rates below 4%. However, if high log prices are expected, higher planting density is supported on SI20 under a 2% discount rate. Interestingly, there is a non-linear relationship as the site index is increased due to the complex change in merchantable volume gains and shift towards lower quality logs in the early stages of stand development (refer to Figures 7 and 8).

Introduction of positive carbon prices (Equations 4 and 5) greatly increases the feasibility of planting more WRC. Under $\text{C\$20/tCO}_2$, planting more is supported on all site indices for discount rates less than 5%. Higher planting is supported under discount rates as high as 5%, 6% and 7% on SI25, SI30, and SI35, respectively. Higher expected log prices do not change these results significantly. Higher carbon prices of $\text{C\$50/tCO}_2$ supports higher planting density on all sites and all conditions except for on SI20 with a discount of 8%. Higher planting is supported on all sites under all conditions for carbon prices of $\text{C\$80/tCO}_2$. This holds even if low future logs prices are considered (25th percentile of distributions in Figures 11).

Table 9. Mean difference in SEV between deer-damaged stands of 1,000 stems per hectare and damaged stands of 800 stems per hectare accounting for timber values only, by site index and discount rates. Only scenarios with positive SEV reported.

	r						
	2%	3%	4%	5%	6%	7%	8%
Site Index	$\tau = \text{C\$0}$						
25	C$66						
35	C$164	C$10					
	$\tau = \text{C\$20}$						
20	C$210	C$94	C$9				
25	C$379	C$223	C$111	C$39			
30	C$419	C$197	C$104	C$47	C$3		
35	C$455	C$303	C$194	C$94	C$35	C$1	
	$\tau=\text{C\$50}$						
20	C$703	C$456	C$292	C$175	C$91	C$28	
25	C$985	C$690	C$492	C$346	C$236	C$153	C$88
30	C$937	C$707	C$533	C$399	C$295	C$212	C$145
35	C$825	C$742	C$609	C$490	C$385	C$298	C$226
	$\tau=\text{C\$80}$						
20	C$1,209	C$839	C$584	C$399	C$265	C$166	C$92
25	C$1,613	C$1,192	C$892	C$667	C$495	C$363	C$260
30	C$1,495	C$1,209	C$960	C$757	C$593	C$461	C$354
35	C$1,291	C$1,186	C$1,034	C$872	C$724	C$593	C$482

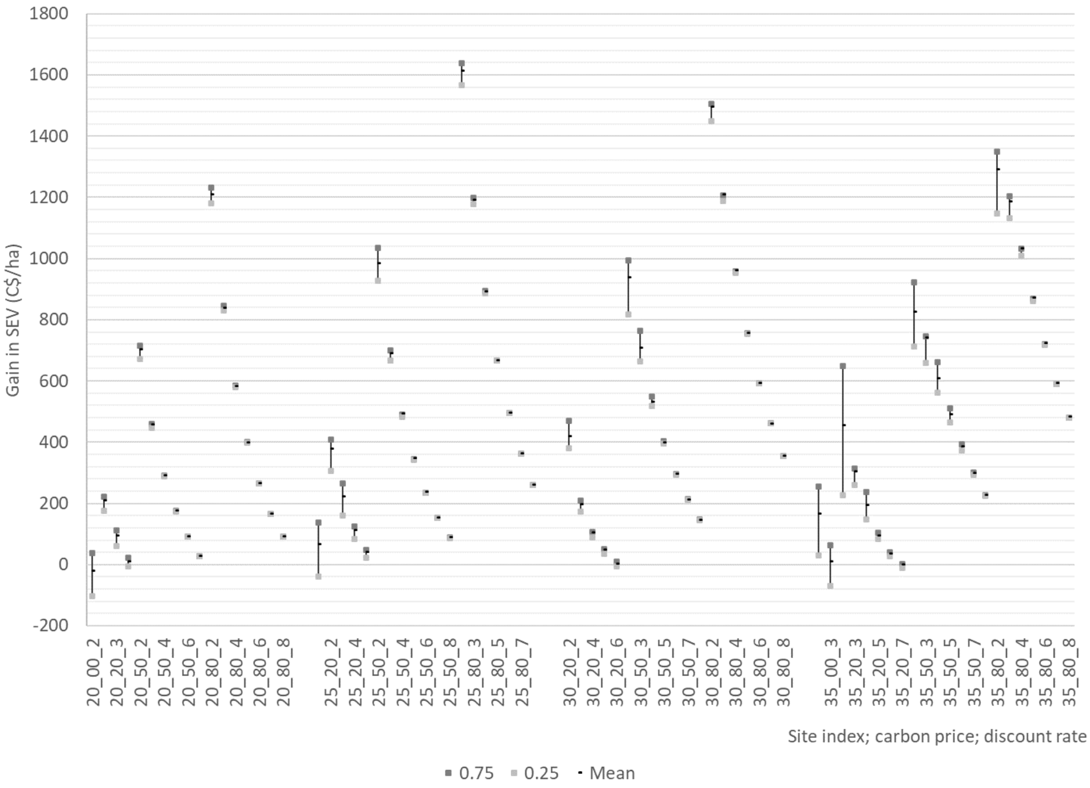

Figure 11. Gain in SEV from mitigating deer damage by increasing planting 1000 stems per hectare instead of 800 by site index, carbon price, and discount rate. Only feasible scenarios at 75th percentile reported.

DISCUSSION AND CONCLUSIONS

Western redcedar is a valuable conifer species, and there is interest in British Columbia and elsewhere to increase efforts to establish plantations, either as pure or mixed stands. However, concerns regarding butt rot and browsing by ungulates has encouraged forest land managers to consider measures to mitigate the impact of these two sources of damage to plantations. Therefore, we consider both of these types of damages in this paper.

Given the high stumping costs, the incremental gain in SEV from removing damages from decay is generally insufficient. This is despite considerable merchantable log volume losses, in particular reductions in high-quality logs. The considerable long delay for the full impact of decay to occur results in highly discounted benefits from decay mitigation, even under discount rates as low as

3%. For public land managers, who may be permitted to consider very low discount rates such as 2%, decay mitigation may be justified, especially on stands of SI25 or higher and high carbon prices. If there are conditions under which stem decay may progress much faster than modelled in this study, then there may be more economic conditions under which stumping might be supported. For private land managers, who often employ much higher real discount rates, stumping is unlikely to be an economically attractive investment, even when decay is expected to progress rapidly. If an option exists for genetic control of butt rot in the future, then the alternative would be viable since this would be deployed by planting and at very little incremental cost.

The results on the elimination of deer damage do not support deer management mitigation actions under timber-only scenarios, except in a few cases of very low discount rates and optimistic future timber prices. The inclusion of carbon prices increases the feasible set of possibilities for some form of deer mitigation. This is largely because of the relatively quick gain in stand biomass, although mainly in the form of low-quality logs. This quick gain in volume translates into an early and sustained cash flow that is not heavily discounted. Consideration of high carbon prices expands the level of expenditures that may be justified across all stand types, especially on public forest lands. For private land managers with higher discount rates and concerns about monetization of carbon sequestration benefits, any incremental management expenditures to mitigate browsing by deer is likely unattractive. Though, perhaps higher damage scenarios encountered under browsing by elk may support modest expenditures. While not considered here, if damage caused by ungulates delays significantly regulatory requirements about stocking standards or harvesting on adjacent mature stands (annual allowable cut effects), then incremental deer management expenditures may be justified.

Finally, an increase in initial planting density was modelled under the assumption that both deer browse and decay would be present. This could be seen as a general strategy to mitigate potential negative impacts from either source of damage. Generally, this strategy is economically feasible under positive carbon prices under a wide set of economic circumstances and site indices. However, if only timber is considered, then this strategy is likely only of interest to public land managers. Given that increased planting only marginally decreases expected SEVs under an assumed no damage scenario, increased planting might be a no regrets strategy on sites already identified to meet the financial requirements of the decision maker.

Not all areas or conditions were examined in this paper. However, we expect these coastal WRC results to hold in interior WRC areas. Stands less than SI20 are unlikely to support expenditures to mitigate decay unless carbon prices are positive and discount rates are very low.

There are several potential areas to improve the analysis of this paper. We consider a limited set of damage from butt rot and deer browse due to limited data. Future research in both areas may uncover a greater range of damage scenarios that could lead to greater range of economic damages and broader support for mitigation strategies. One option that was not considered was tree breeding for genetic gain in yield and deer and disease resistance, which could alter the harvest age and discounting period. Also, this work is stand-level focused and thus extension to a portfolio of stands or forest-level analysis as conducted by Greiss et al. (2015) and Clasen et al. (2011) might provide even greater insights regarding stand mixtures of tree species that are disease tolerant such as WRC and ungulate tolerant such as Douglas-fir.

In this paper, we investigate the economic feasibility of incremental silviculture management to mitigate damage to WRC in coastal BC from both butt rot and deer browse. We considered a broad set of physical and economic conditions and introduced probabilistic modelling of several key economic parameters. The decay mitigation results support a very limited range of conditions for incremental expenditures to control for butt rot. Mitigating damage from deer browse results in a broader set of requirements that support incremental expenditures but are conditioned on explicit recognition of carbon sequestration benefits from these management actions. In general, we find little support for incremental management of western redcedar plantations to mitigate decay or deer predation. However, we do find support for increased planting density on moderate to high site index stands.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest.

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APPENDIX 1 - CALCULATION OF LOG GRADE PREMIUMS AND DISCOUNTS

Detailed information on log grades at the stand level does not exist in the provincial harvest billing system database; only grade volumes and the average stumpage (price) billed are reported. However, the province publishes log price and volume statistics for different log grades traded in the open log market. Therefore, we combine the two pieces of information to derive log grade prices at the stand (pre-logging) corresponding to the log grades produced by the TASS simulations.

Calculation of prices for different log grades simulated from TASS involved several steps.

First, to simplify the analysis, we estimate the annual price and volume proportions of log grades reported in the coastal log market reports for the most commonly reported log grades for WRC (6 log grades). Next, we combined some of the log grade price series by taking the weighted average to reduce the number of log grades to four to be consistent with the TASS simulation log grade outputs. Next, we estimate the price proportions of the log grades relative to saw logs, the highest-grade logs. Finally, we assessed the log grade volume to total volume proportions.

Then, we assumed a one-to-one correspondence between the stand-level log grade volume breakdowns and those observed in the log markets. This led to the following relationship between the average stumpage for a given stand and the log grade breakdown:

$$\hat{w} = P^s \times \rho_s + P^g \times \rho_g + P^u \times \rho_u + P^p \times \rho_p \qquad \text{A1}$$

where $\hat{w}$ is average stumpage price, P_s, P_g, P_u, and P_p are log prices for saw (s), gang (g), chip-and-saw (u), and pulp (p) logs, respectively, and ρ_s, ρ_g, ρ_u, and ρ_p are proportions of total stand volume for each log grade, respectively.

Based on average log grade price proportions calculated from the coastal log market data, we define each non-saw log grade as a function of the saw log price such that

$$P_g = 0.75P^s \qquad \text{A2}$$

$$P_u = 0.44P^s \qquad \text{A3}$$

$$P_g = 0.01P^s \qquad \text{A4}$$

Substituting Equations A2-A4 into Equation A1 we get

$$\widehat{w} = P^s \times \rho_s + 0.75P^s \times \rho_g + 0.44P^s \times \rho_u + 0.01P^s \times \rho_p \qquad \text{A5}$$

where 0.75, 0.44 and 0,01 are the estimated non-saw log price to saw log price proportions for gang, chip-and-saw, and pulp, respectively.

Substituting estimated log-grade volume proportions of 0.3, 0.38, 0.2 and 0.02 for saw, gang, chip-and-saw, and pulp, respectively and solving for saw log price as a function of average timber price we get Equation A6,

$$P^s = \frac{\widehat{w}}{0.3+0.75\times0.38+0.44\times0.2+0.01\times0.02} = \widehat{w} \times 1.337 \qquad \text{A6}$$

Equation A6 was used to transform annual average timber price on the coast of BC into a saw log price. The saw log price was then used to estimate corresponding gang and chip-and-saw log prices that were then used in Equations 2-5.

APPENDIX 2 - SUPPLEMENTARY FIGURES

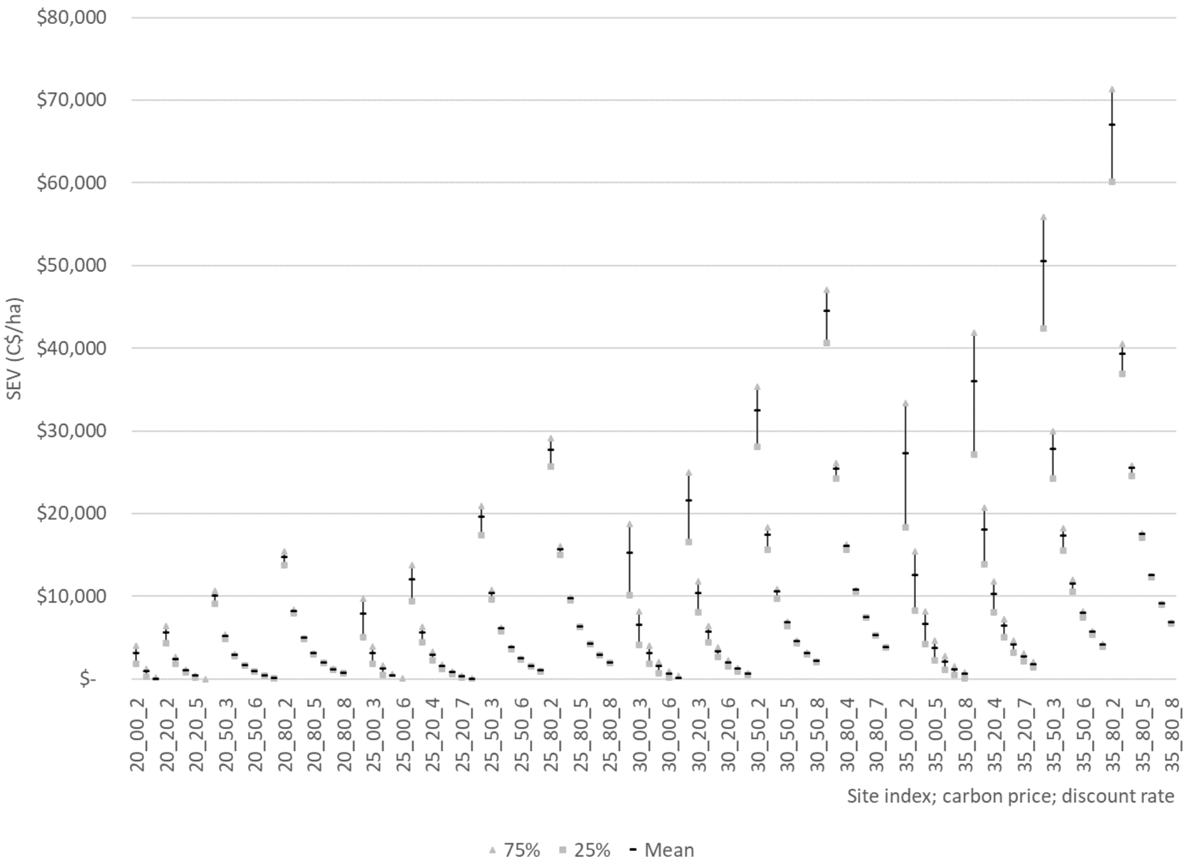

Figure A1. Simulated soil expectation values from planting western redcedar at 800 stems per hectare when there is both deer browse damage and butt rot decay. Mean, 25th and 75th percentile values for all site indices (20, 25, 30, 35), carbon prices (C$0, C$20, C$50, C$80), and discount rates (2 to 8%).

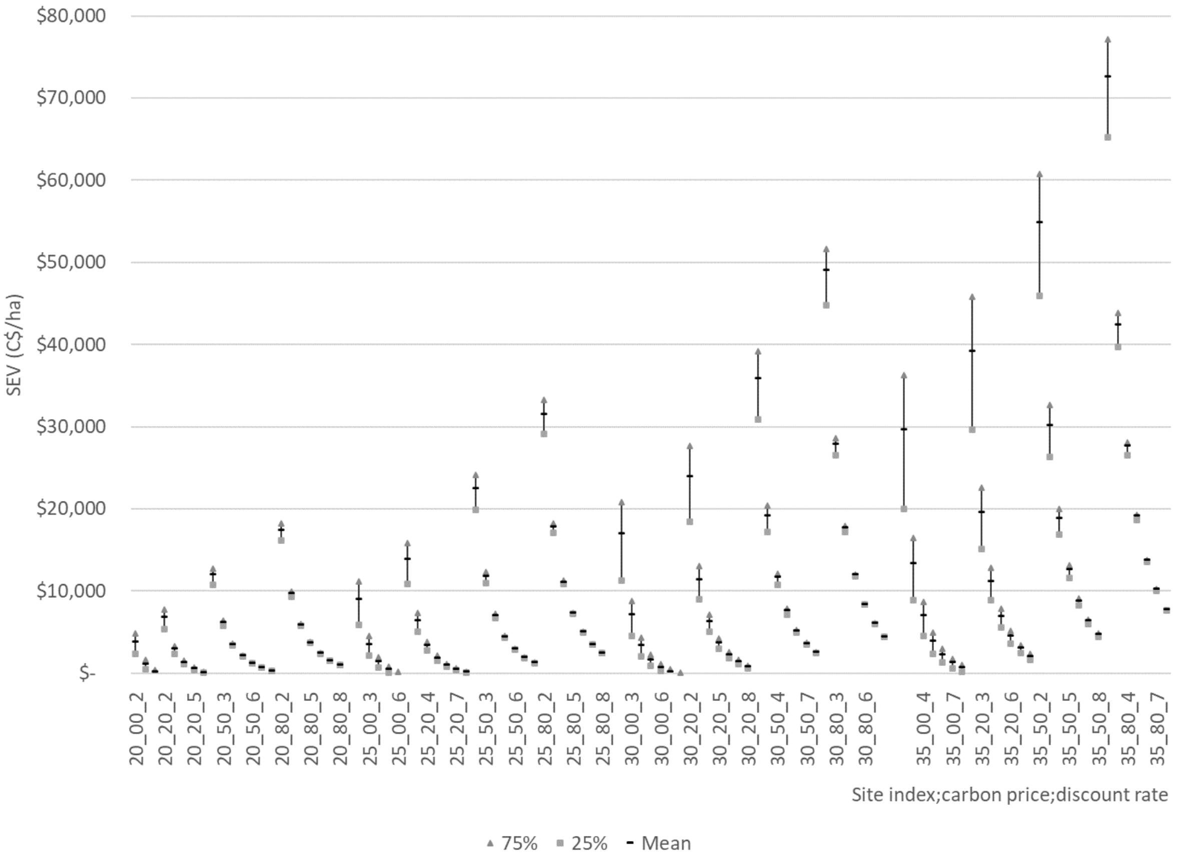

Figure A2. Simulated soil expectation values from planting western redcedar at 800 stems per hectare when there is no deer browse damage nor butt rot decay. Mean, 25th and 75th percentile values for all site indices (20, 25, 30, 35), carbon prices (C$0, C$20, C$50, C$80), and discount rates (2 to 8%).