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Deer browse deterrents and microsite selection influence *Callitropsis nootkatensis* and *Thuja plicata* planting success in Southeast Alaska

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Abstract
Callitropsis nootkatensis (D. Don) Oerst. ex D.P. Little and *Thuja plicata* Donn ex D. Don are ecologically and culturally important tree species in the forests of Southeast Alaska, and there is great interest in maintaining both species across the landscape. This study investigated the impact of browsing and nearby vegetation as a potential limitation for regenerating both species. Three different stock types of both species were planted on five recently clearcut sites. There were four browsing treatments, including a control, chemical repellent, physical protection, and delayed planting until after the spring browsing season. Browsing levels varied among sites, and on sites with higher browsing levels only seedlings with tree shelters benefited from browsing protection. Browsing during the first year was lower for seedlings with obstructions and slash that limited accessibility for deer. Seedlings protected from browsing by tree shelters and slash exhibited greater height and diameter and lower probabilities of seedling mortality after eight growing seasons. On the site with low incidence of severe browsing, most seedlings grew well regardless of browsing treatments. The benefits of larger seedling stock were evident eight years after planting on all sites. The results suggest good regeneration potential for both species in clearcuts with low browsing levels. In contrast, on sites with higher browsing levels, installing tree shelters at time of planting appears to be an effective treatment to reduce the impact of browsing on seedling growth and survival.

Keywords Herbivory · Deer browsing · Tree shelter · Seedling stock · Cedar

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Introduction

Callitropsis nootkatensis (D. Don) Oerst. ex D.P. Little (yellow cedar) and *Thuja plicata* Donn ex D. Don (western redcedar) are prominent long-lived tree species in the temperate rain forests of southern Alaska and British Columbia (Burns and Honkala 1990). Both species are ecologically important, have high timber values, and have a long history of cultural relevance and use (Hennon et al. 2016). The high timber values and interest in spiritual values and other uses by Alaska Natives and First Nations (First Peoples) of the coastal regions have resulted in efforts to regenerate both species to increase the presence of these species in stands across the landscape (Harrington 2010).

In the past few decades, *C. nootkatensis* has been on the decline in parts of its distribution (Hennon et al. 2012, 2016), postulated due to freezing damage in roots as a result of lower snowpack due to climate change (Hennon et al. 2012, 2016). At this time, the full extent of the decline is unknown with the potential for climate change to alter species distribution. Assisted (facilitated) migration has been suggested as a method to maintain adequate populations of the tree species (Hennon et al. 2012, 2021) and any such efforts will likely be dependent upon successful planting of desired species.

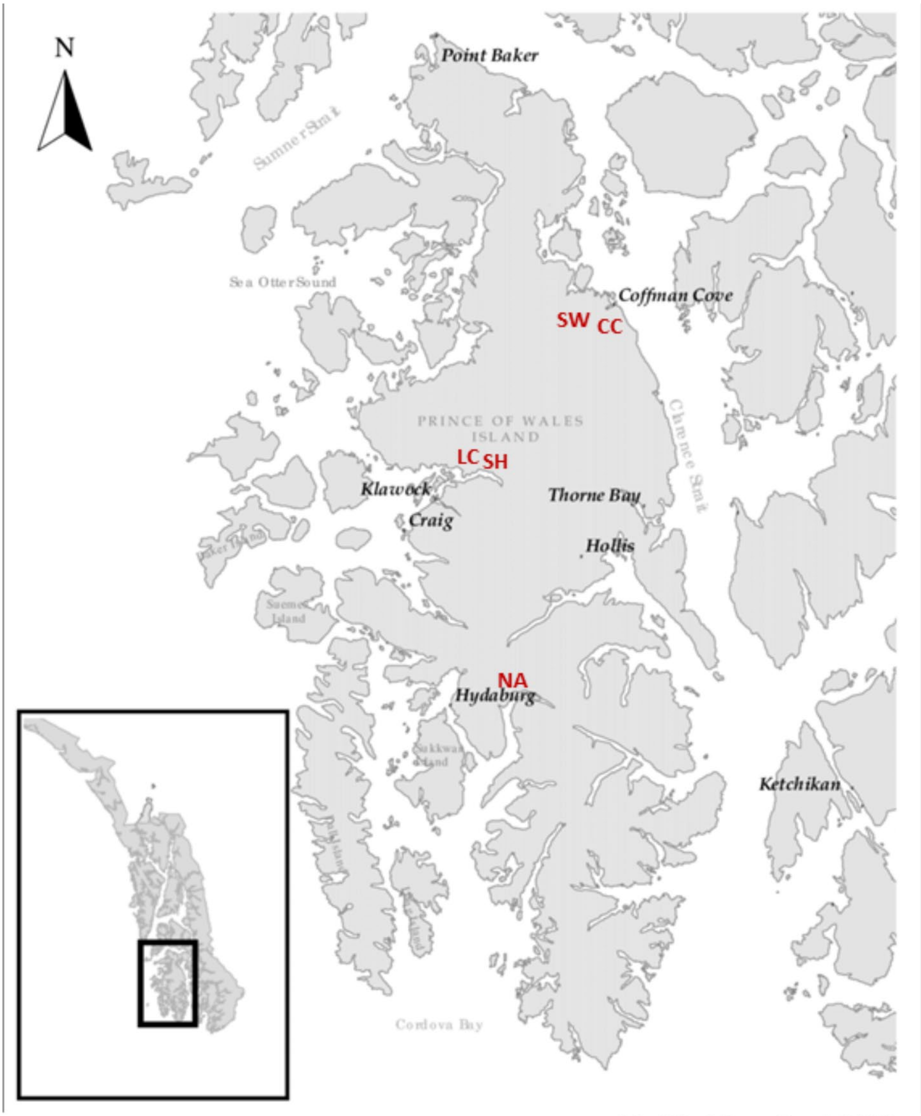
While planting success of *T. plicata* has been considered adequate in many parts of its natural distribution (Curran and Dunsworth 1998; Klinka & Brisco 2009), natural regeneration of both species can be sporadic, due to low seed production, lack of stratification, competition from *Tsuga heterophylla* (Raf.) Sarg. (western hemlock) regeneration, and other factors (DeMeo et al. 1992; Hennon et al. 2012, 2016). One of the main recruitment concerns for both species is seedling browsing (Hennon et al. 2009; Stroh et al. 2008). Deer browse impacts from *Odocoileus hemionus* subsp. *sitkensis* Merriam (Sitka deer) are highly variable and may differ between planted seedlings and natural regeneration. Browsing has contributed to low seedling survival, especially for *C. nootkatensis* (Hennon et al. 2012). Efforts to reduce browsing impacts on cedar seedlings included investigations into foliage chemistry (Burney and Jacobs 2011) and silvicultural practices, such as fertilization (Kimball et al. 2011; Burney and Jacobs 2013), repellents (Deisenhofer and Roasor 2010), and direct browsing protection (Banner and LePage 2008; Hennon et al. 2009). Competition from nearby vegetation has been shown to slow seedling growth, thereby extending the time when seedlings are of small size and thus available for browsing (Cockle and Ettl 2010).

The overall objective of this study was to investigate several factors potentially influencing the establishment of *C. nootkatensis* and *T. plicata* plantations in clearcuts in Southeast Alaska. Specifically, for both species we wanted to determine (1) if the choice of seedling stock type and browsing protection method influenced probabilities of seedlings being browsed in the first year and how this is related to physical obstructions, e.g., slash that limit the accessibility of seedlings to deer browsing, and (2) how seedling species, stock type, browsing treatments, and vegetation near seedlings influence height and diameter growth and seedling mortality after eight years. (3) Finally, we depict what the findings mean in practical terms, i.e., how the treatments influence how many seedlings are likely to contribute to the next stand, as indicated by the development of seedling height over time under different browsing severities.

Materials and methods

Study design

The study was implemented in Southeast Alaska in five recently clearcut sites (Steelhead, Lime Creek, Natzuhini, Coffman Cove, and Sweetwater; listed in sequence from low to high elevation) on Prince of Wales Island (Fig. 1). The sites ranged in elevation from six to



Modified from Turek 2005

Fig. 1 Locations of study sites are marked with red letters:; Steelhead (SH), Lime Creek (LC), Natzuhini (NA), Coffman Cove (CC), and Sweetwater (SW). Map modified from Turek (2005)

260 m above sea level, with average annual precipitation from 2000 to 2400 mm and average annual high temperature from 9.8 to 10.8° C (more details are provided in Table S1).

In each clearcut, we installed three rectangular plots of approximately 50 m x 110 m (Fig. 2). Each plot was split into two subplots planted with either *C. nootkatensis* or *T. plicata*. Four browsing prevention treatments were randomly assigned to each half (sub-subplots). These treatments consisted of a control (NONE), application of Plantskydd Deer Repellent® prior to planting (PDREP), Tree Sentry™ 46 cm photo-degradable conical tree shelters with 90 cm mesh tubing installed immediately after planting (SHELTER), and delayed planting (DELAY), in which seedling planting was delayed for a month to reduce browsing potential during the first spring. Each sub-subplot had three stock types randomly assigned to planting rows (sub-sub-subplots): container plugs (Styro 2; 32–39 cubic cm volume), and two types of bareroot seedlings (plug+1 and plug+2, grown in containers for one year and then in bareroot beds for one and two years, respectively (more details about seed sources and nursery practices are in Textbox 1 in Supplement; Figure S1 depicts the typical rootballs and aboveground sizes of the seedlings at planting time, for information about initial seedling sizes see Table S2). We randomly assigned the stock types to planting rows in plots one, two, and three on the first site. For logistical simplicity we applied the same planting scheme on all sites.

Spacing between the seedlings was 3.3×3.3 m, but logging debris, rocks, and waterlogged areas resulted in wider spacings in many areas. A typical installation had 360 per plot and 1080 seedlings total per site. Due to shortages of *T. plicata* plugs and plug+2s seedlings of both species, the installation at Steelhead had only 9 (plugs) and 10 seedlings (plug+2) per row instead of 15 for these stock types.

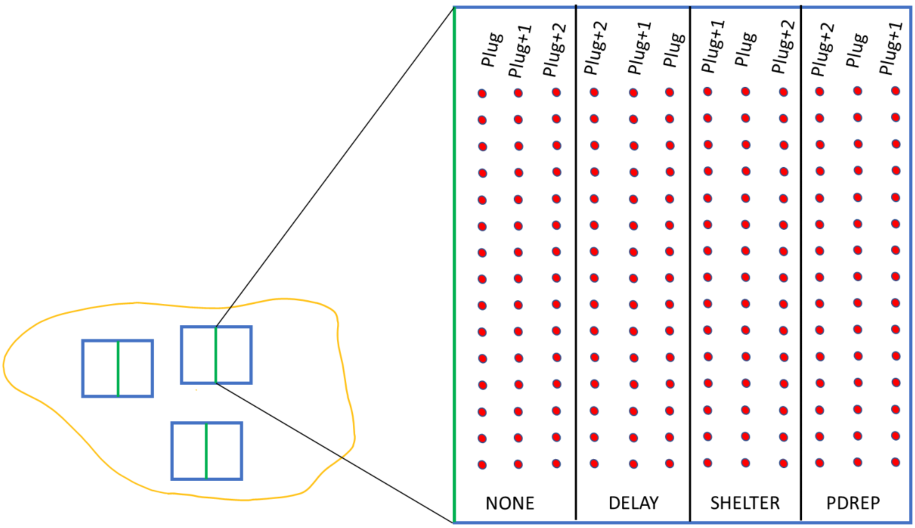


Fig. 2 Conceptual diagram showing the study setup on a single site (yellow line), with three plots (blue rectangles) per site. Each plot was split into two subplots (green line; left side of the diagram) with each subplot randomly assigned to either *Callitropsis nootkatensis* or *Thuja plicata*. Each subplot (right side of diagram) was subdivided into four sub-subplots (black lines) and randomly assigned a browsing treatment (lower label). Within each sub-subplots three rows of 15 seedlings each were assigned a stock type

Study installation

Plot installation began in spring 2013. Most seedlings were planted May 15-May 22, 2013 (initial planting). For the delayed planting treatment, seedlings were planted June 11–13, 2013. The weather conditions on all sites during the initial and delayed planting are presented in Table S1. Vegetation development throughout the growing season varied by and within sites. At the time of initial planting, on Steelhead, the vegetation was greening up, with *Rubus spectabilis* Pursh (salmonberry) and *Polypodiopsida* (ferns) up approximately 30 cm. Some *Luzula* DC *spp.* (wood rushes) were also emerging, but total cover was less than 5% across the entire site. Vegetation development on plot one at Natzuhini was similar to that described above for Steelhead. However, plots two and three had more development of vegetation with salmonberry up 30–50 cm, and some *Sambucus racemosa* L. (red elderberry) already 1 m tall. *Vaccinium* L. (blueberry) was leafing out and forbs, especially *Tiarella trifoliata* L. (foam flower), were already emerging. Vegetation covered 10–15% of these plots. Vegetation at Lime Creek was not as developed as at Steelhead and Natzuhini. *R. spectabilis* and *S. racemosa* were mostly less than 30 cm tall and forbs were not abundant. At Sweetwater, *Vaccinium* L.was leafing out, but forbs were sparse. *Lysichiton americanus* Hultén & H. St. John (skunk cabbage) was also present on the site. Vegetation at Coffman Cove appeared less developed than at Sweetwater. *R. spectabilis* and *S. racemosa* were less than 20 cm, and forbs were not abundant.

Several issues arose which need to be considered when interpreting the study results. The lack of experience of the planting crew in terms of planting larger bareroot seedlings resulted in J-rooting of some seedlings, which was noticed at the time of planting. Although instructions were given to the crew to correct this, it is unlikely that J-rooting was completely avoided. Sites were not cleared of slash prior to planting. Planting in areas with heavy slash or near stumps resulted in some seedlings without sufficient soil coverage around them. Some *C. nootkatensis* plug+2 seedlings were mistakenly root-pruned to 13 cm rather than 25 cm at the nursery. This was not noticed in time and these seedlings with very poor root:shoot ratios were planted. As a result, these seedlings showed evidence of drying out within three days after planting. We do not have numbers of seedlings that have been impacted by these issues. With the exception of the *C. nootkatensis* plug+2 stock type, we had a large enough sample size that it is unlikely that these problems had major impacts on the results.

Measurements

All seedlings were measured within two weeks after planting. Seedlings planted in May 2013 were assessed for survival and browsing in June 2013. After that, seedlings were measured annually in May from 2014 to 2018 and again in May 2021. Basal diameter (mm, measured at 15 cm above groundline) and total seedling height (cm) were measured. Browsing was rated for all seedlings, living or dead, as follows: no browsing (NB), browsed only on terminal (BT), browsing on laterals (BL), browsing on both terminals and laterals (BB), browsing of at least half of the foliage (BH), browsing of at least half of the foliage but leaving more than just a stem (BP), and browsing so that only a stem remained (BS). One year after planting, the ease with which deer can access the seedlings for browsing was assessed using two estimates: access blocking obstructions and overtopping slash. Obstructions were quantified as a numeric value from 0 to 5: no restrictions (0), up to 25% (1), 26–50% (2), 51–75% (3), and 76–100% (4) of the access restricted. Five (5) was even more obstructed, i.e., "in a hole". Slash was quantified as percent cover of residual harvesting slash above the seedlings and was the primary reason for access restrictions with occasionally large rocks impeding access. Because of the relative slow vegetation development on these sites, competition from other vegetation was first assessed two years after planting for living seedlings and seedlings that had died in the past year. Percent overtopping by vegetation was estimated by projecting an upright 60° cone with the basis of the seedling height two years prior (Howard and Newton 1984). Vegetation was also estimated as percent vegetation cover within a 1-meter radius of all seedlings, including cover of grasses, ferns, forbs, residual conifers, planted conifers, sedges, and shrubs. Vegetation was assessed when seedlings were measured.

Statistical analysis

To analyze the impacts of stock type, treatment, and site factors on first-year browsing (Objective 1), we used logistic regression analyses to determine the probability of a seedling being browsed. We chose to use browsing one year after planting, i.e., at the beginning of the second growing season, for this analysis as the effect of chemical treatments, such as Plantskydd Deer Repellent®, will not carry into a second year. For the logistic regression analysis, browsed (regardless of the severity of browsing) or not browsed was the binary response variable and site, species, stock type, browsing treatments, obstructions, and percent slash were the explanatory variables using PROC LOGISTIC in SAS® 9.4. An initial analysis indicated a significant effect of site, driven by the lower browsing levels on Natzuhini (NA) regardless of species, treatment, and stock type. First-year browsing at NA occurred on 18% (n = 182 out of 1023 total) of the seedlings, and only 2% (24/1023) were considered severe. In contrast, at the other sites, browsing occurred on 63% (2507/3976) of the seedlings and 44% (1738/3976) was considered severe. We interpreted this as an indication of low browsing pressure at NA, likely due to hunting access (Martin and Baltzinger 2002). Because data from NA provided little information in regards to Objective 1 and including them would unnecessarily complicate the statistical interpretation (higher order site interactions due to no treatment effect at NA), the browsing analysis used only the remaining sites, i.e., Steelhead (SH), Lime Creek (LC), Coffman Cove (CC), and Sweetwater (SW).

For analyzing the impact of stock type and treatments on total seedling height and basal diameter after eight years (Objective 2), we utilized regression analyses (using PROC MIXED; SAS® 9.4) with plot (nested within site, replications) as a random variable; site, species, browsing treatment, and stock type as fixed effect categorical variables, and vegetation cover and overtopping two years after planting as continuous variables. Because of the lower browsing levels at NA compared to the other sites (SH, LC, CC, and SW), we analyzed seedlings on all sites with higher browsing levels (SH, LC, CC, and SW) separately from NA. We anticipated significant treatment effects at the sites with higher browsing levels and no treatment effects at NA. The analytical setup for the separate analysis of the seedlings on NA was the same, with the exception that site was not included as a variable. Residual analyses indicated that a natural log transformation of basal diameter resulted in a better model for the combined sites, but not for NA. As a measure of fit, we calculated pseudo-R^2 values by comparing actual values to predicted values using PROC REG; SAS® 9.4. Although the intercepts were not significant for the pseudo-R^2 models, they remained in the model to not overinflate the pseudo R^2 values.

To reduce the impact of poor planting and seedling quality, the probability of mortality eight years after planting is based on seedlings alive in June 2013 rather than on seedlings planted May 2013. The probability of seedling mortality eight years after planting was examined by using logistic regression analyses (PROC LOGISTIC SAS® 9.4). As with the analysis of tree sizes, the sites with higher browsing levels (SH, LC, CC, and SW) were analyzed together, and NA was analyzed separately. The LOGISTIC equation used site, type, species, and treatment as categorical factors, and vegetation cover and overtopping two years after planting as continuous factors to predict the probability of mortality.

To determine how many seedlings will likely contribute to the next stand (Objective 3), we examined above what seedling height browsing became minimal in terms of the proportion of the crown removed. After eight years, seedlings were sufficiently tall to allow us to explore 100 cm, 120 cm, 135 cm, and 150 cm as potential target heights. "Target" heights were selected based on observations in the field and results from other studies (e.g., Witmer et al. 1995; Saunders and Puettmann 1999). As with earlier analyses, we presented the average for seedlings on all sites with higher browsing levels separately from the seedling data from NA. To simplify the presentation of the results, seedlings were then sorted by the browsing categories based on the assessment eight years after planting into low (NB, BT), moderate (BL, BB), and severe (BH, BP, BS) browsing.

In addition, to depict how early browsing influences seedling development over time, we sorted the species by their browsing impacts measured either one or two years after planting into the same three categories of no or minor browsing (Low), moderate browsing (Mod), and Severe browsing (see above). Hereby, seedlings were grouped in categories based on the highest browsing category measured in either year 1 or 2. Using only seedlings alive eight years after planting, we calculated means for each measurement period, species, and browsing category, and displayed the data in graphs. On NA only one seedling was in the *C. nootkatensis* plug+2, severely browsed category and this category was not included in the graphs. All other categories had at least 5 seedlings.

Results

Seedling browsing during the first year

Browsing in the month after planting was minor. Less than 1% of the seedlings were browsed between the time of planting (May 2013) and June 2013, when the seedlings in the DELAY treatment were planted. The browsing assessment in May 2014 indicated that treatment, site, and ease of access by deer influenced seedling browsing during the first year (Table 1). For better interpretation of the statistical results in practical terms, Table 2 presents browsing averages by species, treatment, and stock type for the categories of low, moderate, and severe browsing. The SHELTER treatment was the only treatment that reduced browsing over the first winter (Table 2).

These results were consistent across SH, LC, CC, and SW. and for both species. Over all stock types, *T. plicata* was browsed more than *C. nootkatensis*. However, this result was

Table 1 Results of the Logistic analysis showing the impacts of various factors on the probability of browsing [P(browsing)] one year after planting. Sites with higher browsing levels included Steelhead (SH), Lime Creek (LC), Coffman Cove (CC), and Sweetwater (SW). Species abbreviation for *Callitropsis nootkatensis* and *Thuja plicata* are Cn and Tp, respectively. Browsing treatments included a no treatment control (NONE), an application of Plantskydd Deer Repellent® prior to planting (PDREP), installation of tree shelters (SHELTER) and planting delayed until after the spring browsing season (DELAY). Obstruction was measured as physical blockage of deer being able to reach the seedlings. Slash was the cover of residual material left after harvesting. Odds Ratios estimates and Wald confidence intervals are provided in Table S3

	Level	Estimate[a]	Error	DF	Chi-Square	Pr>Chi-Square
Intercept		1.33	0.11	1	155.49	<0.0001
Site	SH	0.21	0.08	1	8.12	0.0044
	LC	-0.20	0.07	1	8.59	0.0034
	CC	0.15	0.07	1	4.41	0.0358
	SW	0		.		
Species	Cn	0		.		
	Tp	0.42	0.04	1	104.25	<0.0001
Stock type	Plug	0.75	0.06	1	151.35	<0.0001
	Plug+1	0.30	0.06	1	28.77	<0.0001
	Plug+2	0				
Browsing treatment	NONE	0.64	0.07	1	79.57	<0.0001
	PDREP	0.76	0.07	1	111.53	<0.0001
	SHELTER	0		.		
	DELAY	0.62	0.07	1	80.18	<0.0001
Obstruction		-0.26	0.04	1	42.34	<0.0001
Slash		-0.02	0.004	1	21.50	<0.0001

[a] P(browsing) = 1/[1 + exp(-(1.33 + Site + Species + Stock type + Browsing treatment – 0.26 (Obstruction) – 0.02 (Slash)))]

confounded by the low browsing for *C. nootkatensis* plug+2 stock type, which was likely due to the low vigor and smaller amounts of foliage (see description in the Method section of issues complicating interpretation of study results). To examine this, we re-analyzed the data with *C. nootkatensis* plug+2 stock type removed from the analyses and then again with both species plug+2s removed. In both cases, species became nonsignificant in the regressions (Tables S4 through S7). Generally, larger stock types (Plug+1 and Plug+2) resulted in lower amounts of severe browsing (Table 2), and this trend was significant when only examining *T. plicata* stock types. In addition, the ease of accessibility was influential, with higher obstruction levels and higher amounts of slash adjacent to the seedlings reducing the probability of browsing (Table 1).

Seedling performance eight years after planting

The results confirmed our decision to separate sites with high and with low browsing levels for the remaining analyses. On the sites with higher browsing levels, the influence of the browsing treatments, as already evident in the first year (Tables 1 and 2), was still reflected in mortality trends (Tables S8 through S12) as well as average seedling sizes eight years later (Tables 3 and 4; Tables S13 through S17). The seedlings in tree shelters had the largest average height and basal diameters, with relatively little difference between the other treatments and the no-treatment control (Table 3). *T. plicata* seedlings were bigger than *C. nootkatensis*. Choosing the larger planting stock resulted in larger seedlings eight years later. Competition by overtopping vegetation, as measured in year two, resulted in lower height and diameter eight years after planting. In addition, basal diameter after eight years was also reduced by vegetation cover (Table 3).

Seedling mortality showed trends like those found for seedling size. The impacts of the browsing treatments on the probability of seedling mortality were still significant (Table 4), but less so than for growth. Seedlings that were protected with a tree shelter resulted in lower probability of mortality after eight years. *C. nootkatensis* (Cn) seedlings had higher mortality than *T. plicata* (Tp) seedlings, overall. *C. nootkatensis* plug+2s had the greatest mortality. Competing vegetation also resulted in higher mortality (Table 4).

On NA, i.e., the site with lower browsing levels, the trends regarding the growth performance of species and stock types were similar to trends found on the other sites, with *T. plicata* on average performing better than *C. nootkatensis* for height, but not diameter, and overtopping reducing growth (Table 5). However, in contrast to the sites with higher browsing levels, the estimates for the browsing treatment other than SHELTER were positive rather than negative (Tables 3 and 5). Therefore, seedlings that had received the SHELTER treatment did not outperform other browsing treatments. Instead, seedlings treated with PDREP showed the largest height and basal diameter. Similarly, the benefit of larger stock types was less pronounced after eight years, especially in regard to basal diameter (Table 5). At NA, mortality after eight years did not show differences based on browsing treatments. Otherwise, trends were similar to those found on the other sites (Table 4).

Practical implications

In terms of practical implications of our findings, Fig. 3 shows the average height development of seedlings through year eight for a site with higher browsing level (Sweetwater,

Table 2 Mean percentage of seedlings browsed one year after planting (%), separated by low (Low; no browsing or only terminal browsed), moderate (Mod; browsing on laterals or browsing on both terminals and laterals), and severe browsing (Severe; browsing at least half of the foliage, browsing of at least half of the foliage but leaving more than just a stem, or browsing so that only a stem remained) categories. Other abbreviations are as described in Table 1

Browse Treatment	Browse level	*Callitropsis nootkatensis*			*Thuja plicata*		
		Plug	Plug+1	Plug+2	Plug	Plug+1	Plug+2
Steelhead, Lime Creek, Coffman Cove, Sweetwater							
NONE	Low	11	35	67	15	24	22
	Mod	5	14	18	9	7	16
	Severe	84	51	15	76	69	63
PDREP	Low	14	16	81	10	23	30
	Mod	9	20	9	16	23	27
	Severe	77	64	9	73	53	43
SHELTER	Low	90	92	93	83	78	77
	Mod	1	5	5	4	19	20
	Severe	9	3	2	13	3	3
DELAY	Low	12	10	81	16	26	30
	Mod	8	24	8	10	31	40
	Severe	79	66	10	74	43	30
Natzuhini							
NONE	Low	84	96	86	71	66	67
	Mod	14	4	14	18	27	30
	Severe	2	0	0	11	7	2
PDREP	Low	98	95	94	73	66	78
	Mod	2	5	6	13	30	18
	Severe	0	0	0	13	5	4
SHELTER	Low	100	100	100	96	98	100
	Mod	0	0	0	4	2	0
	Severe	0	0	0	0	0	0
DELAY	Low	87	98	87	91	84	91
	Mod	9	2	11	7	16	9
	Severe	4	0	2	2	0	0

other sites showed similar, but less pronounced trends) and a site with lower browsing levels (Natzuhini). Note, that on this site even trees that were moderately or heavily browsed during at least one of the first two years performed on average very well compared to all seedlings on the other sites.

Table 6 shows the proportions of seedlings for the two species that had reached the respective target heights after eight years on sites with higher browsing levels. The vast majority of seedlings were below the target heights and the vast majority of these seedlings were moderately or heavily browsed even in year eight. In contrast, the trend was reversed for seedlings taller than the target heights eight years after planting, as more of them were only slightly browsed in year eight. It appears that if *T. plicata* seedlings reached a height between 120 and 135 cm after eight years, the severity of subsequent browsing to the point that more than 50% of the crown was removed basically became negligible (<5%). Fewer *C. nootkatensis* seedlings reached the target heights after 8 years, making it more difficult to determine the strength of the conclusions in this regard.

Discussion

The study results highlighted the challenges when planting cedar in clearcut areas in Southeast Alaska with high deer populations and associated higher browsing levels. They confirmed that not only *C. nootkatensis* (Hennon et al. 2009), but also *T. plicata* are prime browse species for *O. hemionus* (Stroh et al. 2008), and that browsing levels and associated impacts on seedlings vary across the landscape (Hennon et al. 2009). The results also confirmed that browsing not only leads to growth reductions, but also to increased mortality (Banner and LePage 2008). In contrast to growing under a closed old-growth canopy (Stroh et al. 2008) where growth is lower under heavy shade (Cockle and Ettl 2010), seedlings on our study sites in clearcut areas on Prince of Wales Island grew quite well in absence of browsing even without weed control release treatments (see also Mainwaring and Maguire 2010). This suggests opportunities for regeneration of both species even without browsing treatments in areas with limited deer browsing (Hennon et al. 2009).

Browsing impacts selected crop tree species and can have long-term impacts on development of plant assemblages (Boulanger et al. 2015) and diversity (Burkepile et al. 2017), and both cedar species were affected by browsing in the study areas. This confirmed Banner and LePage's (2008) findings that vegetation composition after clearcutting developed to reflect nearby old-growth composition, with the notable exception that *T. plicata* regeneration was lacking in their study area. Regeneration success, even in areas with deer browsing, is often influenced by a variety of factors and their interactions, including overstory canopies or gaps (Walters et al. 2016) and competing vegetation. For example, in areas with light herbicide treatments, deer and elk browsing suppressed competing vegetation and thus increased seedling survival of (unprotected) *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir) in clearcuts in Oregon (Stokely et al. 2018). Also, mechanical removal of competing vegetation improved the effectiveness of tree shelters in protecting seedlings from browsing (Yagi 2022). Our study sites received no herbicide or other release treatments, allowing vegetation development after harvesting. We could not detect any indirect beneficial impacts of browsing on competing vegetation, and overtopping vegetation had a negative impact on the growth and survival of seedlings of both species, as has been shown for other species in

Table 3 Regression results for seedling size eight years after planting on sites with higher browsing levels. Abbreviations are as described in Table 1. Vegetation cover within one meter of the seedlings and overtopping were estimated two years after planting. The height and basal diameter models were both highly significant ($P<0.0001$) and had pseudo-R^2 of 0.44 and 0.45, respectively

	Level	Estimate	Error	DF	t value	Pr > |t|
Height[a]						
Intercept		180.76	6.85	8	26.40	<0.0001
Site	SH	18.28	8.75	8	2.09	0.0700
	LC	67.46	7.87	8	8.57	<0.0001
	CC	18.01	7.79	8	2.31	0.0494
	SW	0				
Species	Cn	0	0	.	.	.
	Tp	32.11	2.88	2316	11.14	<0.0001
Stock type	Plug	-74.23	3.67	2316	-20.25	<0.0001
	Plug+1	-51.43	3.60	2316	-14.29	<0.0001
	Plug+2	0	.	.	.	.
Browsing treatment	NONE	-87.90	3.88	2316	-22.64	<0.0001
	PDREP	-84.87	3.80	2316	-22.32	<0.0001
	SHELTER	0	.	.		.
	DELAY	-90.88	3.83	2316	-23.73	<0.0001
Vegetation cover (yr 2)		-0.06	0.06	2316	-1.05	0.2925
Overtopping (yr 2)		-0.50	0.14	2316	-3.65	0.0003
Basal diameter[b]						
Intercept		3.305	0.047	8	70.78	<0.0001
Site	SH	0.179	0.059	8	3.02	0.0166
	LC	0.584	0.053	8	11.00	<0.0001
	CC	0.193	0.052	8	3.68	0.0062
	SW	0				
Species	Cn	0	.	.		.
	Tp	0.191	0.020	2316	9.50	<0.0001
Stock type	Plug	-0.527	0.025	2316	-20.64	<0.0001
	Plug+1	-0.214	0.025	2316	-8.53	<0.0001
	Plug+2	0		.		.
Browsing treatment	NONE	-0.551	0.027	2316	-20.40	<0.0001
	PDREP	-0.541	0.026	2316	-20.44	<0.0001
	SHELTER	0		.		.
	DELAY	-0.556	0.027	2316	-20.86	<0.0001
Vegetation cover (yr 2)		-0.0022	0.0004	2316	-5.47	<0.0001
Overtopping (yr 2)		-0.0095	0.00096	2316	-9.92	<0.0001

[a]Height (cm) = 180.76 + Site + Species + Stock type + Browsing reatment −0.06 (Vegetation cover) −0.50 (Overtopping)

[b] ln Basal Diameter (mm) = 3.305 + Site + Species + Stock type + Browsing treatment −0.0022 (Vegetation cover) −0.0095 (Overtopping)

productive environments (Rose et al. 1999; Wagner and Radosevich 1998). Given the large impact of browsing on seedlings of both cedar species on our sites, it appears unlikely that any potential benefit in terms of herbivores suppressing competing vegetation would have had a substantial impact on the regeneration of both species, as was found in other settings with high browsing levels (Brousseau et al. 2017; Stokely et al. 2018).

Table 4 Results of the logistic regression for probability of seedling mortality [P(Mortality)] eight years after planting on sites with higher browsing levels and Natzuhini only. Odds Ratios and Wald confidence intervals are presented in Table S18 and S19 for sites with higher browsing levels and Natzuhini only, respectively. Variables and abbreviations are as described in Tables 1 and 3

	Level	Estimate	Error	DF	Chi-Square	Pr>Chi-Square
Steelhead, Lime Creek, Coffman Cove, and Sweetwater[a]						
Intercept		-1.75	0.10	1	287.27	<0.0001
Site	SH	1.86	0.09	1	437.97	<0.0001
	LC	-0.49	0.09	1	32.49	<0.0001
	CC	-0.58	0.09	1	44.52	<0.0001
	SW	0	.	.	.	.
Species	Tp	-0.62	0.05	1	144.28	<0.0001
	Cn	0	.	.	.	.
Stock type	Plug	0.26	0.07	1	13.52	0.0002
	Plug+1	-0.22	0.07	1	10.02	0.0015
	Plug+2	0	.	.	.	.
Browsing treatment	NONE	0.20	0.09	1	5.19	0.0228
	PDREP	0.34	0.08	1	17.53	<0.0001
	SHELTER	0	.	.	.	.
	DELAY	0.43	0.08	1	26.71	<0.0001
Vegetation cover (yr 2)		0.009	0.002	1	18.38	<0.0001
Overtopping (yr 2)		0.03	0.003	1	86.82	<0.0001
Natzuhini only[b]						
Intercept		-3.39	0.36	1	89.64	<0.0001
Species	Tp	-0.62	0.21	1	9.01	0.0027
	Cn	0				
Stock type	Plug	0.17	0.25	1	0.49	0.4842
	Plug+1	-0.88	0.31	1	8.10	0.0044
	Plug+2	0	.	.	.	.
Browsing treatment	NONE	0.07	0.33	1	0.04	0.8414
	PDREP	-0.09	0.32	1	0.07	0.7846
	SHELTER	0	.	.	.	.
	DELAY	0.20	0.32	1	0.39	0.5332
Vegetation cover (yr 2)		-0.02	0.008	1	4.33	0.0374
Overtopping (yr 2)		0.04	0.007	1	36.39	<0.0001

[a]P(Mortality) = 1/[1 + exp(-(-1.75 + Site + Species + Stock type + Browsing treatment + 0.009 (Vegetation cover) + 0.03 (Overtopping)))]

[b]P(Mortality) = 1/[1 + exp(-(-3.39 + Species + Stock type + Browsing treatment – 0.02 (Vegetation cover) + 0.04 (Overtopping)))]

Installing tree shelters was the only treatment that consistently reduced browsing in our study. This treatment has been effective in a variety of settings (Redick and Jacobs 2020), including *C. nootkatensis* (Hennon et al. 2009), other conifers, e.g., *P. menziesii* (DeYoe and Schaap 1984), hardwoods, e.g., *Quercus virginiana* Mill. (live oak) (Thyroff et al. 2022), as well as shrubs, e.g., *Purshia tridentate* (Pursh) DC. (Antelope bitterbrush) (Johnson and Okula 2006). However, Abe's (2022) meta-analysis indicated a publication bias resulting in overrepresentation of beneficial effects and contrasting results have been attributed to

Table 5 Regression results for seedling size eight years after planting Natzuhini, i.e., the site with lower browsing levels. Variables and abbreviations are as described in Tables 1 and 3. The height and basal diameter models were both highly significant (P<0.0001) and had pseudo R^2 of 0.28 and 0.18, respectively

	Level	Estimate	Error	DF	t value	Pr > |t|
Height[a]						
Intercept		266.27	12.43	2	21.41	0.0022
Species	Cn	0				
	Tp	34.14	6.27	873	5.44	<0.0001
Stock type	Plug	-46.91	8.06	873	-5.82	<0.0001
	Plug+1	-26.00	8.10	873	-3.21	0.0014
	Plug+2	0	.	.	.	.
Browsing treatment	NONE	20.08	8.77	873	2.29	0.0223
	PDREP	28.52	8.73	873	3.27	0.0011
	SHELTER	0	.	.	.	.
	DELAY	15.94	8.88	873	1.80	0.0729
Vegetation cover (yr 2)		1.14	0.13	873	8.58	<0.0001
Overtopping (yr 2)		-2.45	0.19	873	-12.97	<0.0001
Basal diameter[b]						
Intercept		51.08	2.99	2	17.10	0.0034
	Cn	0				
	Tp	-2.4330	1.57	873	-1.54	0.1227
Stock type	Plug	-6.04	2.02	873	-2.98	0.0029
	Plug+1	2.93	2.03	873	1.44	0.1503
	Plug+2	0	.	.	.	.
Browsing treatment	NONE	6.23	2.20	873	2.83	0.0048
	PDREP	9.22	2.19	873	4.21	<0.0001
	SHELTER	0	.	.	.	.
	DELAY	5.76	2.23	873	2.59	0.0098
Vegetation cover (yr 2)		0.13	0.03	873	4.10	<0.0001
Overtopping (yr 2)		-0.55	0.05	873	-11.53	<0.0001

[a]Height (cm) = 266.27 + Species + Stock type + Browsing Treatment + 1.14 (Vegetation cover) – 2.45 (Overtopping)

[b]Basal Diameter (mm) = 51.08 + Species + Stock type + Browsing Treatment + 0.13 (Vegetation cover) – 0.55 (Overtopping)

logistical issues, e.g., to shelters being not high enough (Keeton 2008; Nomiya et al. 2022). Issues with tree shelters encountered on our study sites included a few shelters that were removed by bears, resulting in these seedlings being browsed (L. Cole, pers. observation). However, the small numbers of shelters removed were not enough to reduce the overall effectiveness of the treatment in our study. In addition, as trees grew within the meshed shelters tangling of branches and leaders lead to deformities on some seedlings (especially on LC and NA; S. Spores and L. Cole, pers. observation), which has also been found on other sites for *C. nootkatensis* (Hennon et al. 2009), *Cryptomeria japonica* (L.f.) D. Don (Japanese cedar) (Nomiya et al. 2022), and hardwood species (Thyroff et al. 2022). Although photo-degradable, tree shelters and mesh have not deteriorated after 8 years, leading to concerns of girdling or abrasion of tree stems in future years.

The application of chemical repellants has a history of mixed results and showed no benefits in several experiments, (DeYoe and Schaap 1987), including our study (see also Andelt

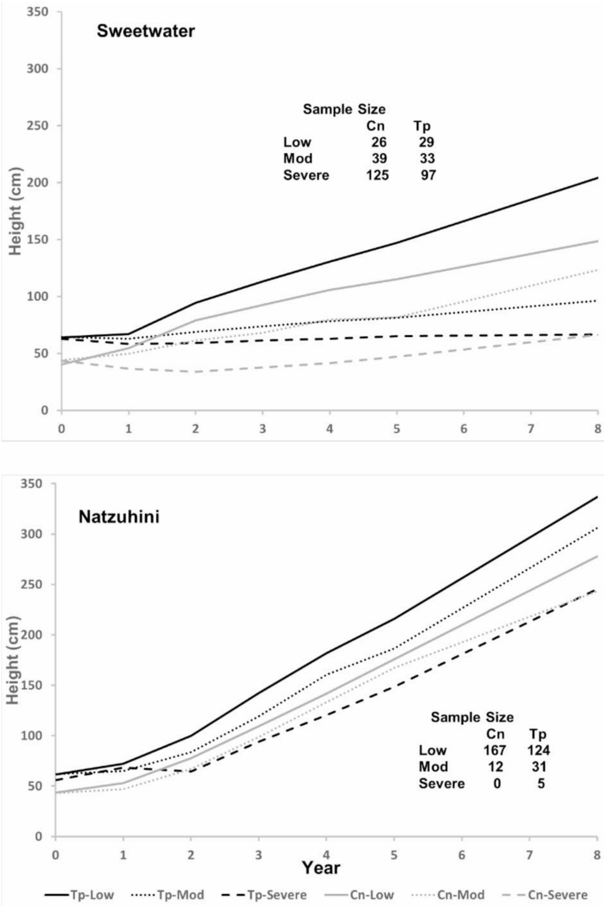


Fig. 3 Average height development during the first eight years for *Callitropsis nootkatensis* (Cn) and *Thuja plicata* (Tp) seedlings on the Sweetwater and Natzuhini study sites. Seedlings of all stock types were sorted into groups with no or minor (Low), moderate (Mod), and Severe browsing during years one and two

Table 6 Percentages of live seedlings that were smaller or larger than the four target heights eight years after planting. Seedlings were sorted based on the browsing levels in year eight into three categories (see abbreviation in Table 2 heading). Data are only from sites with higher browsing levels, i.e., Steelhead, Lime Creek, Coffman Cove, and Sweetwater

	Callitropsis nootkatensis				*Thuja plicata*			
Browsing level	**100 cm**	**125 cm**	**135 cm**	**150 cm**	**100 cm**	**125 cm**	**135 cm**	**150 cm**
Seedlings smaller than target height (%)								
Low	8.9	12.3	14.3	15.8	4.9	6.5	7.8	9.0
Moderate	36.8	40.0	42.9	44.8	17.7	22.2	25.2	26.8
Severe	23.2	24.3	24.3	24.4	30.5	34.5	36.4	37.2
Seedlings taller than target height (%)								
Low	19.1	15.8	13.7	12.3	27.8	26.3	25.0	23.8
Moderate	10.6	7.4	4.5	2.6	11.6	7.1	4.1	2.5
Severe	1.4	0.2	0.2	0.1	7.5	3.4	1.6	0.8

et al. 1992). A major disadvantage of these types of treatments is that they are rather short-lived (Witmer et al. 1995) and need to be applied repeatedly. We applied the chemical only right before planting and did not see any benefits in terms of browsing reduction one year later. Due to the high rainfall on the study sites, it is likely that the repellant only lasted a few months. Therefore, our study does not provide information on how effective this treatment would be if applied immediately prior to the winter/early spring browsing season.

The study results also confirmed the role of physical obstructions in terms of the probability that individual seedlings are browsed (Ameztegui and Coll 2015; Saunders and Puettmann 1999). Vegetation, micro-topography, and slash were effective at blocking deer access to the seedlings and thus led to lower browsing levels during the first year. Various ground treatments that removed vegetation and slash were not effective in reducing herbivory by moose in Newfoundland (Charron and Hermanutz 2017), indicating that the presence of slash may serve as a deterrent to browsing. While in other studies plant species differed in their ability to discourage deer browsing (Saunders and Puettmann 1999), we did not have a sufficient set of different conditions to investigate this issue.

Our results confirmed the importance of the choice of stock types, vigorous planting stock, and proper planting procedures (Hennon et al. 2009). In our case, the *C. nootkatensis* seedling performance of Plug+2 seedlings showed that larger planting stock, which generally performed better under browsing pressure (Yagi 2022), requires additional attention in terms of seedling handling, e.g., root pruning and planting. Even though we eliminated seedlings that died within the first month after planting in our data base, the quality problems of the Plug+2 seedlings still showed eight years after planting. Regarding the result that smaller stock types were more likely to be browsed, we do not have specific information about the seedling chemical composition of foliage, which has been shown to differ based on nursery practices (Burney et al. 2012). These authors suggested that selected monoterpenes could be related to different browsing attractiveness of fertilized versus non-fertilized seedlings. It is not known how these results apply to *C. nootkatensis* as foliar chemistry or the response of the chemistry to fertilization or browsing has been shown to vary among different species (Burney and Jacobs 2018) and even among *T. plicata* families (Burney et al. 2012) and by locations, e.g., between Haida Gwaii and the adjacent mainland (Vourc'h et al. 2001). However, in the dominant tree species in temperate rainforests in Chile, the presence of secondary metabolites was not related to the degree of browsing (Salgado-Luarte et al. 2023).

In terms of long-term development, seedling heights that have been shown to result in a shift in browsing trends ranged from 60 cm, which was the height when *Odocoileus virginianus* (Zimmeman) (white tailed deer) browsing shifted from leader to lateral branches of *Pinus strobus* L. (white pine) seedlings (Saunders and Puettmann 1999) to 1.5 m for *Odocoileus hemionus* (Rafinesque) (mule deer) and *Cervus* (Erxleben) (elk) browsing (Witmer et al. 1995). In our study, seedlings outgrew major browse impacts once they reach more than 120 cm in height. In contrast, shelters with a height of 140 cm apparently are not sufficiently high enough to completely prevent browsing by *Cervus nippon* (Temminck) (sika deer) in Japan (Nomiya et al. 2022). Browsing impacts are not the only factor affecting long-term development. It should be noted that other tree species, e.g., *Alnus rubra* Bong. (red alder), *Picea sitchensis* (Bong.) Carrière (Sitka spruce), and *T. heterophylla*, regenerated naturally on the study sites and in many places were overtopping seedlings of both cedar species after eight years (L. Cole, pers. observation). In these places, release or pre-commercial thinning treatments are likely necessary to encourage growth of planted and natural regeneration of *C. nootkatensis* and *T. plicata* (Devine and Harrington 2009).

Conclusion

Our findings suggest opportunities and also highlight challenges for planting both cedar species in clearcuts in Southeast Alaska. In any setting with higher browsing levels, planting vigorous seedlings and installing tree shelters appears crucial for successful regeneration. However, maintenance and later removal of shelters may be necessary to prevent stem deformities. Such reforestation efforts also may be most successful on higher quality sites (Banner and LePage 2008). Other studies have shown the benefit of targeted fertilization applications (Weetman et al. 1993), especially in conjunction with treatments that reduce competing vegetation (Devine and Harrington 2009), but the implications of those treatments in terms of browsing attractiveness and impacts are unknown.

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Author contributions Author contribution The project was conceived by MN and the study was designed by LC and KJP. The field sites were established and measured by LC. Analyses were designed and carried out by LC in consultations with KJP. Manuscript writing was led by KJP and LC, who also prepared the figures.

Data Availability The data underlying this article will be shared on reasonable request to Liz Cole.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Disclaimer Mentioning of product names does not indicate any endorsement.

References

Abe T (2022) Effects of treeshelter on seedling performance: a meta-analysis. J For Res 27:171–181

Ameztegui A, Coll L (2015) Herbivory and seedling establishment in Pyrenean forests: influence of micro- and meso-habitat factors on browsing pressure. For Ecol Manage 342:103–111

Andelt WF, Baker DL, Burnham KP (1992) Relative preference of captive cow elk for repellent-treated diets. J Wildl Manage 56:164–173

Banner A, LePage P (2008) Long-term recovery of vegetation communities after harvesting in the coastal temperate rainforests of northern British Columbia. Can J for Res 38:3098–3111

Boulanger V, Baltzinger C, Saïd S, Ballon P, Picard J-F, Dupouey J-L (2015) Decreasing deer browsing pressure influenced understory vegetation dynamics over 30 years. Ann For Sci 72:367–378

Brousseau M, Thiffault N, Beguin J, Roy V, Tremblay J-P (2017) Deer browsing outweighs the effects of site preparation and mechanical release on balsam fir seedlings performance: implications to forest management. For Ecol Manage 405:360–366

Burkepile DE, Fynn RWS, Thompson DI, Lemoine NP, Koerner SE, Eby S, Hagenah N, Wilcox KR, Collins SL, Kirkman KP, Knapp AK, Smith MD (2017) Herbivore size matters for productivity–richness relationships in african savannas. J Ecol 105:674–686

Burney OT, Jacobs DF (2011) Ungulate herbivory of regenerating conifers in relation to foliar nutrition and terpenoid production. For Ecol Manage 262:1834–1845.

Burney OT, Jacobs DF (2013) Ungulate herbivory of boreal and temperate forest regeneration in relation to seedling mineral nutrition and secondary metabolites. New For 44:753–768

Burney OT, Jacobs DF (2018) Species selection a fundamental silvicultural tool to promote forest regeneration under high animal browsing pressure. For Ecol Manage 408:67–74

Burney OT, Davis AS, Jacobs DF (2012) Phenology of foliar and volatile terpenoid production for Thuja plicata families under differential nutrient availability. Env Exp Bot 77:44–52

Burns RM, Honkala BH (eds) (1990) Silvics of North America. US Department of Agriculture, Forest Service, Washington, DC

Charron L, Hermanutz L (2017) Simplicity is key: restoration protocols for nonregenerating forests degraded by overabundant herbivores. Rest Ecol 25:432–441

Cockle A, Ettl G (2010) Survival and growth of Western Redcedar and Douglas-fir planted in a variable retention harvest unit in the western Cascades, Washington. In: A Tale of Two Cedars: International Symposium on Western Redcedar and Yellow-Cedar. Victoria, B.C. May 24–28, 2010. United States Department of Agriculture General Technical Report PNW-GTR-828, Harrington C. (edt.) pp 115–120

Curran M, Dunsworth B (1988) Coastal western red cedar regeneration: problems and potentials. IN: Western red cedar-does it have a future. Vancouver, B.C. July 13-14th 1987.; Conference proceedings, N. Smith (edt.) pp 20–32. https://rngr.net/publications/fnn/2008-winter/new-nursery-literature/coastal-western-red-cedar-regeneration-problems-and-potentials

Deisenhofer F, Rasor C (2010) Six-year western redcedar (*Thuja plicata*) height growth performance in southwest Washington. In: A Tale of Two Cedars: International Symposium on Western Redcedar and Yellow-Cedar. Victoria, B.C. May 24–28, 2010. United States Department of Agriculture General Technical Report PNW-GTR-828, Harrington C. (edt.), pp 158–159

DeMeo T, Martin J, West RA (1992) Forest plant association guide: Ketchikan Area, Tongass National Forest. United States Department of Agriculture, Forest Service,, Juneau. Alaska Region R10-MB-210

Devine WD, Harrington CA (2009) Western redcedar response to precommercial thinning and fertilization through 25 years posttreatment. Can J For Res 39:619–628

DeYoe DR, Schaap W (1984) Comparison of 8 physical barriers used for protecting Douglas-fir seedlings from deer browse In, Proceedings of the Eastern Wildlife Damage Control Conference, pp 77–93

DeYoe D, Schaap W (1987) Effectiveness of new formulations of deer repellants tested in Douglas-fir plantations in the Pacific Northwest. Tree Planter's Notes 38:22–25

Harrington CA (2010) In: A tale of two Cedars: International Symposium on Western Redcedar and Yellow-Cedar, vol General Technical Report PNW–GTR–828. United States Department of Agriculture, Forest Service, Victoria, B.C. May 24-28, 2010

Hennon PE, McClellan MH, Spores SR, Orlikowska EH (2009) Survival and growth of planted yellow-cedar seedlings and rooted cuttings (stecklings) near Ketchikan, Alaska. West J Appl For 24:144–150

Hennon PE, D'Amore DV, Schaberg PG, Wittwer DT, Shanley CS (2012) Shifting climate, altered niche, and a dynamic conservation strategy for yellow-cedar in the north Pacific Coastal rainforest. BioSci 62:147–158

Hennon PE, McKenzie CM, D'Amore DV, Wittwer DT, Mulvey RL, Lamb MS, Biles FE, Cronn RC (2016) A climate adaptation strategy for conservation and management of yellow-cedar in Alaska United States Department of Agriculture, Forest Service, General Technical Report PNW-GTR-917

Hennon PE, Frankel SJ, Woods AJ, Worrall JJ, Ramsfield TD, Zambino PJ, Shaw DC, Ritóková G, Warwell MV, Norlander D, Mulvey RL (2021) Applications of a conceptual framework to assess climate controls of forest tree diseases. For Path 51(6):e12719

Howard KM, Newton M (1984) Overtopping by successional coast-range vegetation slows Douglas-fir seedlings. J For 178–180

Johnson GR, Okula JP (2006) Antelope bitterbrush reestablishment: a case study of plant size and browse protection effects. Native Plants J 7:125–133

Keeton WS (2008) Evaluation of tree seedling mortality and protective strategies in riparian forest restoration. North J Appl For 25:117–123
Kimball BA, Pfund F, Gourley M, Griffin DL, Russell JH (2011) Silvicultural attempts to induce browse resistance in conifer seedlings. Int J For Res
Klinka K, Brisco D (2009) Silvics and silviculture of coastal western redcedar: a literature review Special. Report Series-Ministry of Forests and Range, British Columbia
Mainwaring D, Maguire D (2010) Growth of western red cedar with Douglas-fir in young plantations in western Oregon In: A Tale of Two Cedars: International Symposium on Western Redcedar and Yellow-Cedar. Victoria, B.C. May 24–28, 2010. United States Department of Agriculture General Technical Report PNW-GTR-828, Harrington C. (edt.) pp 109–114
Martin JL, Baltzinger C (2002) Interaction among deer browsing, hunting, and tree regeneration. Can J For Res 32(7):1254–1264
Nomiya H, Abe T, Kanetani S, Yamagawa H, Otani T, Sakai A, Yoneda R (2022) Survival and growth of japanese cedar (*Cryptomeria japonica*) planted in tree shelters to prevent deer browsing: a case study in southwestern Japan. J For Res 27:200–205
Redick CH, Jacobs DF (2020) Mitigation of deer herbivory in temperate hardwood forest regeneration: a meta-analysis of research literature. Forests 11:1220
Rose R, Ketchum JS, Hanson DE (1999) Three-year survival and growth of Douglas-fir seedlings under various vegetation-free regimes. For Sci 45:117–126
Salgado-Luarte C, González-Teuber M, Madriaza K, Gianoli E (2023) Trade-off between plant resistance and tolerance to herbivory: mechanical defenses outweigh chemical defenses. Ecol 104:e3860
Saunders MR, Puettmann KJ (1999) Use of vegetational characteristics and browsing patterns to predict deer damage in eastern white pine (*Pinus strobus*) plantations. North J Appl For 16:96–102
Stokely TD, Verschuyl J, Hagar JC, Betts MG (2018) Herbicides and herbivory interact to drive plant community and crop-tree establishment. Ecol Appl 28:2011–2023. https://doi.org/10.1002/eap.1777
Stroh N, Baltzinger C, Martin J-L (2008) Deer prevent western redcedar (*Thuja plicata*) regeneration in old-growth forests of Haida Gwaii: is there a potential for recovery? For Ecol Manage 255:3973–3979
Thyroff EC, Burney OT, Oliet JA, Redick CH, Jacobs DF (2022) Toward identifying alternatives to fencing for forest restoration: tube shelters outperform mesh shelters for deer browse protection of live oak, *Quercus virginiana*. Land 11:966
Turek M (2005) Prince of Wales Island subsistence steelhead harvest and use pattern. US Fish and Wildlife Service, Office of Subsistence Management, Subsistence Fisheries Resource Monitoring Program Final Report for Study: 03-651
Vourc'h G, Martin J-L, Duncan P, Escarré J, Clausen TP (2001) Defensive adaptations of Thuja plicata to ungulate browsing: a comparative study between mainland and island populations. Oecologia 126:84–93
Wagner RG, Radosevich SR (1998) Neighborhood approach for quantifying interspecific competition in coastal Oregon forests. Ecol Appl 8:779–794
Walters MB, Farinosi EJ, Willis JL, Gottschalk KW (2016) Managing for diversity: harvest gap size drives complex light, vegetation, and deer herbivory impacts on tree seedlings. Ecosphere 7:e01397
Weetman GF, McDonald MA, Prescott CE, Kimmins JP (1993) Responses of western hemlock, Pacific silver fir, and western red cedar plantations on northern Vancouver Island to applications of sewage sludge and inorganic fertilizer. Can J For Res 23:1815–1820
Witmer GW, Sayler RD, Pipas MJ Repellent trials to reduce reforestation damage by pocket gophers, deer, and elk. National Wildlife Research Center Repellents Conference, Special Symposium Denver, Colorado, August 8–10, 1995. Proceedings, Mason R (1995) (edt.), pp 321–332. https://digitalcommons.unl.edu/nwrcrepellants/40/
Yagi T (2022) The combined effects of tree shelters, large stock and vegetation control on the early growth of conifer seedlings. J For Res 27:206–213