

Article

Eight-Year Survival and Growth of Sakhalin Fir (*Abies sachalinensis*) Seedlings with One Weeding Operation: Impact of Mechanical Site Preparation, Vegetation Release, Summer Planting, Stock Type, and Forwarder Trail

Hisanori Harayama ^{1,*}, Ikutaro Tsuyama ², Takeshi Yamada ¹, Mitsutoshi Kitao ², Naoyuki Furuya ^{2,†}, Kenichi Yazaki ², Tetsuto Sugai ², Akira Uemura ¹, Shozo Sasaki ³ and Hajime Utsugi ¹

¹ Forestry and Forest Products Research Institute, Tsukuba 305-8687, Japan; kenchan@ffpri.affrc.go.jp (T.Y.); akirauem@ffpri.affrc.go.jp (A.U.); utsugi@ffpri.affrc.go.jp (H.U.)

² Hokkaido Research Center, Forestry and Forest Products Research Institute, Sapporo 062-8516, Japan; itsuyama@ffpri.affrc.go.jp (I.T.); kitao@ffpri.affrc.go.jp (M.K.); nufuruya@affrc.go.jp (N.F.); kyazaki@ffpri.affrc.go.jp (K.Y.); sugai922@ffpri.affrc.go.jp (T.S.)

³ KITARIN Lab, Sapporo 064-0913, Japan; sho.ssk@kitarin.org

* Correspondence: harahisa@ffpri.affrc.go.jp

† Current address: Agriculture, Forestry and Fisheries Research Council Secretariat, Ministry of Agriculture, Forestry and Fisheries, Chiyoda-ku, Tokyo 100-8950, Japan.



Citation: Harayama, H.; Tsuyama, I.; Yamada, T.; Kitao, M.; Furuya, N.; Yazaki, K.; Sugai, T.; Uemura, A.; Sasaki, S.; Utsugi, H. Eight-Year Survival and Growth of Sakhalin Fir (*Abies sachalinensis*) Seedlings with One Weeding Operation: Impact of Mechanical Site Preparation, Vegetation Release, Summer Planting, Stock Type, and Forwarder Trail. *Forests* **2024**, *15*, 1012. <https://doi.org/10.3390/f15061012>

Academic Editors: Mohammed S. Lamhamedi, Damase P. Khasa and Steeve Pepin

Received: 2 May 2024

Revised: 28 May 2024

Accepted: 4 June 2024

Published: 11 June 2024



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Abstract: In Hokkaido, northern Japan, bareroot Sakhalin fir seedlings are conventionally planted in spring and fall, following strip site preparation that alternates managed and unmanaged strips. However, this method requires seven years of weeding due to encroachment of evergreen dwarf bamboo. Given diminishing forest labor availability, a shortage of workers for planting and weeding operations has become a problem in reforestation following clearcutting. We examined whether comprehensive mechanical site preparation (MSP) could reduce weeding frequency by preventing regrowth of dwarf bamboo and whether container seedlings could extend the planting season into summer. Over eight years, the survival and growth of summer-planted bareroot and container seedlings were examined on a fully MSP-treated site with only one weeding operation in the fifth year. Full-site MSP resulted in a shift of the vegetation from dwarf bamboo to deciduous plants, leading to high survival and growth rates of Sakhalin fir seedlings despite minimal weeding. Container seedlings exhibited superior establishment and maintained higher survival rates over eight years than bareroot seedlings. However, planting on the forwarder trail decreased seedling growth, and ultimately decreased survival under rare summer drought. Our findings indicate that container seedling summer planting and full-site MSP may represent an alternative approach to reforestation of Sakhalin fir, potentially reducing the need for weeding and extending the planting season.

Keywords: bareroot seedlings; container seedlings; height growth; root collar diameter growth; soil compaction; weeding

1. Introduction

Vegetation management is a crucial silvicultural practice for forest establishment, regeneration, and growth [1–3]. The survival and growth of target tree seedlings can be profoundly affected by vegetation competition [4–6]. Evergreen dwarf bamboo, with its low environmental requirements, robust clonal reproduction through rhizomes, and adaptability to heavy snow, often sustains prolonged dominance in the understory of cool temperate forests in Japan (Figure S1a,b). This competitive strength prevents tree regeneration in natural forests and hampers the survival and growth of planted seedlings in plantation forests (Figure S1c–e) [7–10]. Consequently, dwarf bamboo management is paramount for successful regeneration and reforestation in Japan. The use of herbicides

for forest vegetation management is increasingly prohibited or restricted regionally and globally owing to environmental concerns [11–13], including in Japan. Vegetation release using motor-manual brush cutters is more socially acceptable than herbicides, causing fewer disruptions to forest ecosystems [14–16]. However, this method tends to be less effective and more costly in competition control compared with herbicides [14,17]. Therefore, in regions with thriving weeds due to humid climates, the cost for vegetation release using motor-manual brush cutters can be prohibitively high, accounting for up to half of the reforestation cost in the initial decade. This financial burden discourages forest owners from reforestation after clearcutting in Japan [18].

Sakhalin fir (*Abies sachalinensis* (F. Schmidt) Mast.) is an important timber tree species in Hokkaido, northern Japan [19–21], alongside Japanese larch (*Larix kaempferi* (Lamb.) Carrière). Given its slower growth rate relative to Japanese larch, Sakhalin fir typically undergoes seven years of consecutive weeding from planting until surpassing the surrounding vegetation height [10], whereas Japanese larch requires four consecutive years of weeding [22]. To minimize labor and weeding costs, Sakhalin fir reforestation operations are typically undertaken in recurring strip areas comprising managed and unmanaged zones, as opposed to whole-site plantation (Figure 1a) [23]. Site preparation, planting, and subsequent weeding transpire within a 3 m wide strip, with the adjacent 4 m wide strip remaining unaltered. After clearcutting and site preparation, dwarf bamboo predominantly takes over unmanaged strips as competing vegetation, with heights of 3 m for *Sasa kurilensis* (Rupr.) Makino & Shibata, 2 m for *Sasa senanensis* (Franch. & Sav.) Rehder, and 1 m for *Sasa nipponica* (Makino) Makino & Shibata, contingent on snow cover depth [10,24]. For Sakhalin fir reforestation, 2000–2500 seedlings per hectare are planted in two rows within each managed strip. This maintains a mere 0.75 m distance between the unmanaged strip's border and the planted seedlings (Figure 1a). Dwarf bamboo exhibits leaf physiological traits adaptable to both well-lit and shaded environments [25] and quickly adapts its leaf physiology to abrupt light intensity changes following overstory tree removal [26]. Consequently, the planted seedlings are susceptible to being overshadowed by vigorously growing dwarf bamboo in unmanaged strips, leading to its rapid invasion of the managed strip via rhizome spreading.

Mechanical site preparation (MSP) before reforestation entails clearing vegetation and logging debris from the forest floor to facilitate planting and modifying the soil to support seedling survival and growth while managing competing vegetation. This approach serves as a chemical herbicide alternative on a global scale [12,27,28]. In Japan, MSP is occasionally implemented through topsoil scarification using an excavator-mounted bucket and mulching with a forest mulcher attached to an excavator for postlogging vegetation management [29,30], although manual site preparation remains predominant. In birch forests where the upper trees have been lost due to logging or natural disturbances in Hokkaido, both bucket scarification MSP and mulching MSP have effectively suppressed dwarf bamboo regeneration, enabling the emergence of deciduous perennials and shrubs, previously stifled by dense dwarf bamboo cover [31,32]. As Sakhalin fir is highly shade-tolerant [33–35], similar to other American and European *Abies* species [36,37], its seedlings' survival and growth may be less impacted by deciduous vegetation compared with evergreen dwarf bamboo. Thus, applying MSP across the plantation and restraining dwarf bamboo regeneration could substantially curtail the need for frequent weeding in Sakhalin fir plantations.

Various factors influence seedling survival and growth during reforestation, including seedling type and quality [30,38], as well as soil compaction resulting from heavy forestry vehicle use [39,40]. In Japan, the past decade has seen the introduction of container seedlings, aiming to extend the planting season to include summer and counteract the decline in forest labor availability [18,41]. Container seedlings generally suffer less transplant shock and exhibit greater drought resistance than bareroot seedlings [38]. Nevertheless, information on Sakhalin fir container seedling survival and growth, particularly after summer planting, remains insufficient. Additionally, Hokkaido's forested regions, featuring

gentle slopes and the largest collection of high-performance forestry machinery in Japan, frequently employ a ground-based cut-to-length (CTL) system combining a harvester and a forwarder for logging efficiency [42]. This operational focus, while improving efficiency, often neglects the adverse impact of machinery on Japanese forest soils [43], subsequently affecting seedling performance post-reforestation [44,45].

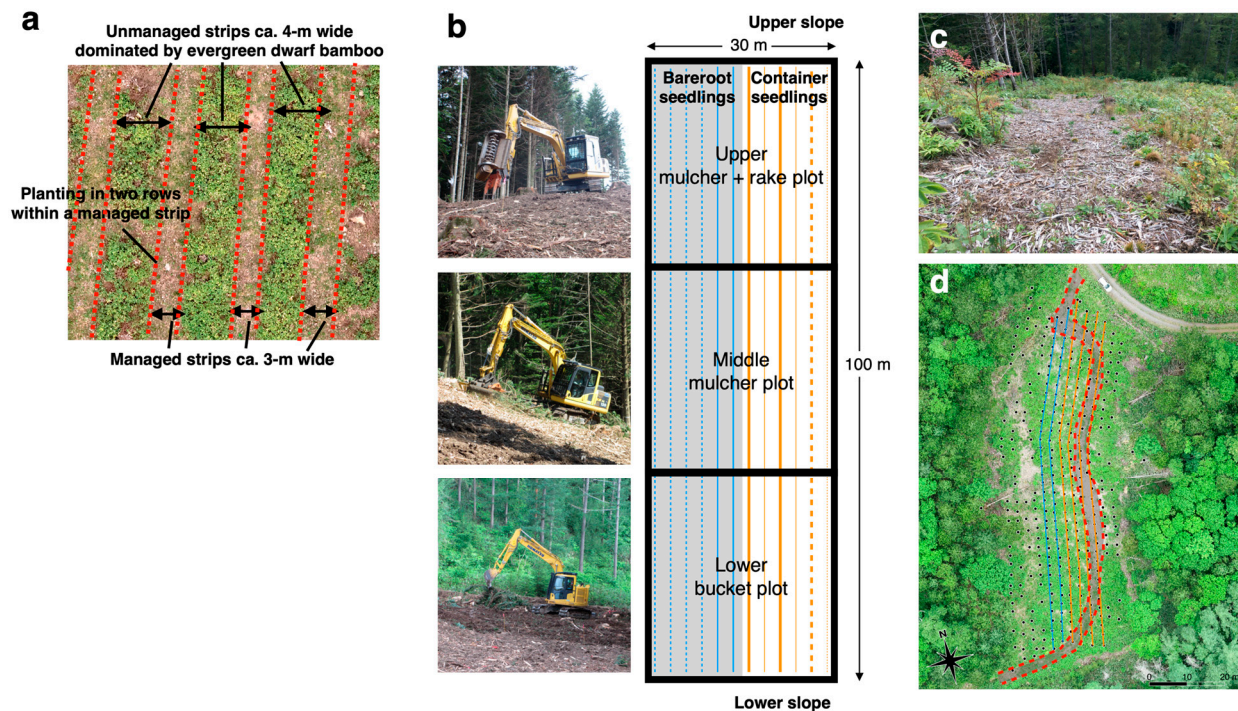


Figure 1. (a) An orthoimage of the typical Sakhalin fir plantation with strip practices. (b) A schematic diagram of the study site. (c) A photograph of vegetation on the forwarder trail in October 2017. (d) An orthoimage of the study site captured in June 2018. In (a), site preparation, planting, and weeding are performed only in the 3 m wide managed strips (bounded by the red dashed line) and not in the adjacent 4 m wide unmanaged strips. In (b), blue and orange lines represent planting rows of Sakhalin fir bareroot and container seedlings, respectively. Solid and dashed lines indicate the surveyed and not-surveyed planting rows. Thick and thin orange lines indicate rows planted with JFA300 and JFA150 container seedlings, respectively. In (d), the gray band surrounded by the red dashed lines represents the forwarder trail. The solid blue and orange lines represent the planting rows of bareroot and container seedlings, respectively, that were surveyed. Black dots indicate the positions of planted seedlings.

In this context, we hypothesized that all-encompassing reforestation site MSP targeting dwarf bamboo removal could reduce weeding demands for planted Sakhalin fir seedlings by delaying regeneration of rival vegetation. We also examined the prospect of extending the planting season into summer through container seedling deployment. To address these aims, we explored the eight-year survival and growth of summer-planted Sakhalin fir, using both bareroot and container seedlings. We restricted weeding to a single intervention in the fifth year during eight years in the reforested area, with whole-site MSP approaches after harvest by a harvester and forwarder CTL system. The main objective of this study was to determine whether Sakhalin fir seedlings could flourish with markedly reduced weeding frequency, accomplished by suppressing the resurgence of the robust competitor, dwarf bamboo, through comprehensive site-wide MSP. Furthermore, we conducted quantitative assessments of summer planting's effects on seedling survival and growth, distinguished by seedling type (bareroot vs. container), as well as the effects of weeding on vegetation release and the repercussions of forwarder trails using generalized linear models (GLMs) and linear mixed models (LMMs).

2. Materials and Methods

2.1. Study Site, Site Preparation, and Planting Design

The study site, with a haplic brown forest soil type, is situated in a ~50-year-old Sakhalin fir plantation with a slope of ~14°–20° in Shimokawa town, Hokkaido (44°16′40″ N, 142°41′42″ E; 370 m above sea level). It has a humid continental (hemiboreal) climate (Dfb), as per the Köppen classification. The 1991–2020 records from the nearest weather station (44°18′ N, 142°37′ E; 140 m above sea level) indicated an average annual air temperature of 5.4 °C. Monthly mean daily maximum and minimum air temperatures were 25.0 °C in August and −8.8 °C in January, with an annual precipitation of 965 mm. The heaviest snow cover, 116 cm, occurred in March.

Between 30 June and 7 July 2015, approximately 0.3 ha (30 m wide × 100 m long) underwent CTL harvesting. This system used a harvester (350.1, Komatsu Ltd., Tokyo, Japan; base machine: PC138US, Komatsu Ltd.) and a forwarder with front-wheel and rear-crawler (F801, IHI Co., Tokyo, Japan). Subsequently, the following two MSP methods were applied: 0.5 m³ capacity bucket scarifying MSP (PC120, Komatsu Ltd.) and mulching MSP (MINI-BMS 125, Seppi, Mezzolombardo, Italy) using excavators (Figure 1b). The harvested area was divided into three plots (each approximately 30 m wide × 30 m long): (1) lower-slope bucket scarification MSP (hereafter, called the lower-bucket plot; Figure 1b), (2) mid-slope mulcher MSP without raking (middle-mulcher plot), and (3) upper-slope mulcher MSP with raking (upper-mulcher + rake plot). In the latter plot, planting spots were perforated with a rake attachment to the mulcher for manual planting facilitation, involving cutting dwarf bamboo rhizomes and soil loosening. Notably, machine operations occurred in rainy weather with occasional interruptions during the first half of the 30 June to 4 July operational period (Figure S2).

The study site was vertically divided along the slope. Bareroot Sakhalin fir seedlings were placed on one side, whereas container seedlings were positioned on the other (Figure 1b). On 8 July 2015, post-MSP, planting occurred in a 2.58 m × 2.58 m spacing (equivalent to 1503 plants ha^{−1}). Container seedlings grown in JFA300 (cell capacity: 300 mL; density: 178 seedlings m^{−2}; Zenbyouren, Tokyo, Japan) and JFA150 (cell capacity: 150 mL; density: 292 seedlings m^{−2}; Zenbyouren) were planted each in alternating rows. This led to six rows of each seedling type (three each of JFA300 and JFA150) along the slope direction. Weeding occurred solely in summer 2019, the fifth-year post-planting, using motor-manual brush cutters in line with the previous year's survey findings of dwarf bamboo height matching Sakhalin fir seedlings.

2.2. Field Measurements

For each stock type (bareroot, JFA300, and JFA150), study individuals were selected from the two rows closest to the study site's centerline ($n = 71$ for bareroot; $n = 70$ each for JFA300 and JFA150, Figure 1b) to minimize shading effects from the surrounding forest. Seedling height (measured to 1 cm accuracy with a ruler) and root collar diameter (RCD; measured to 0.1 mm accuracy with a digital caliper) were assessed on 8 July 2015, post-planting, and at each growing season's conclusion (late fall October–November or the ensuing early spring May) until the eighth-year post-planting (final measurement on 4 October 2022). Additional data, including vitality status, animal damage, and motor-manual brush cutter miscutting during weeding, were recorded for each seedling. The height/RCD (H:D) ratio was calculated to assess stem shape. For annual relative growth rates of height (RGR_H) and RCD (RGR_D) in each year, $RGR = \ln(S_2) - \ln(S_1)$ [46] was used, where S_2 and S_1 represent the size (height or RCD) of the seedling at season's end and start, respectively. Notably, data equivalence was assumed between late fall and the subsequent early spring, given minimal seedling height and diameter change over winter, i.e., the nongrowing season. Therefore, RGR was presented as an annual figure for convenience, despite calculations not being founded on precise one-year intervals. Notably, RGR for the first planting year spanned from July 8, immediately after planting, to the growing

season end, a period shorter by two months compared with the second, which spanned eight years due to summer planting.

Recovery of vegetation removed during MSP in 2015 was assessed three years later on 11 June 2018. No weeding was performed between MSP and vegetation assessment. For each of the central two rows of container seedlings where survival and growth were examined ($n = 63$), the species and the maximum height of the most dominant plant covering Sakhalin fir seedlings were documented. Competing vegetation was categorized as evergreen dwarf bamboo and deciduous trees, shrubs, and herbs.

During the October 2017 survey, we observed suppressed vegetation and reduced planted seedling growth on forwarder trails where multiple return trips had been made during the harvest (Figure 1c). Subsequently, we noted whether the studied seedlings grew on the forwarder trail. In June 2018, aerial photographs of the study site were captured using an unmanned aerial vehicle (Phantom 4 Pro, DJI, Shenzhen, China), yielding an orthoimage to confirm suppressed vegetation growth locations on the forwarder trail (Figure 1d).

2.3. Statistical Analyses

2.3.1. Initial Seedling Distribution and Statistical Approach

Table 1 provides the initial count of measured seedlings. Distribution of seedlings within and outside the forwarder trail was unbalanced, especially with a limited number of bareroot seedlings inside the trail (Figure 1d). The effect of the trail was unintended in the original experimental design. Owing to evident forwarder trail impact on seedling growth, the statistical analysis was divided into two patterns. First, only container seedling data were analyzed to assess the forwarder trail effect, excluding bareroot seedlings seldom placed on the trail. Second, analysis of stock type differences (bareroot vs. container seedlings) only considered data representing planting outside the trail.

Table 1. Summary of the number of seedlings investigated per plot, categorized by combined mechanical site preparation (MSP) methods, slope position, and forwarder trail.

Plot Name	Lower-Bucket		Middle-Mulcher		Upper-Mulcher + Rake		Total
MSP Slope position Forwarder trail	Bucket Lower		Mulcher Middle		Mulcher + Rake Upper		
	Outside	Inside	Outside	Inside	Outside	Inside	
Bareroot	21	0	26	0	22	2	71
Container-JFA150	14	6	17	9	17	7	70
Container-JFA300	14	6	17	9	16	8	70
Subtotal	49	12	60	18	55	17	
Total	61		78		72		211

It was not possible to differentiate the MSP method and slope location effects owing to site size limitations and thus the plot effects included both MSP and slope location effects. The soil at the lower part of the slope will likely be more humid, which will result in the subsequent vegetation being more prolific or exhibiting a different species composition, regardless of the MSP method employed. Preliminary analysis indicated minimal plot effects on height, RCD, H:D ratio, RGR_H , and RGR_D over the eight-year study period (Figures S3 and S4), and no significant effect on two-year ($p = 0.15$) or eight-year survival ($p = 0.14$). Hence, the plot effect was treated as a random factor whenever possible, and when not possible, it was included as an explanatory variable but not nearly discussed in this study.

R version 4.2.2 [47] was used to conduct all statistical analyses. Significance was set at $\alpha = 0.05$.

2.3.2. Analyses of Differences between Stock Types and between Years

Height, RCD, H:D ratio, RGR_H, and RGR_D differences among stock types per year were evaluated using Tukey's multiple comparison test through the "multcomp" package's *glht* function [48] for data outside the forwarder trail. Additionally, differences in RCD, H:D ratio, RGR_H, and RGR_D across years were examined via Tukey's multiple comparison test for year effects in LMMs. These models featured year and stock type as fixed effects and plot as a random effect. Tukey's multiple comparison test was performed for each fixed effect.

2.3.3. Analyses of Survival Rate and Height Growth Using GLMs and LMMs

The effects of stock type (bareroot or container seedlings), initial seedling size, and forwarder trail on survival rates in the second and eighth years post-planting were assessed through GLMs with binomial distributions using the "brglm2" package's *glm* function, based on Firth's bias correction for complete separation [49]. Survival in the second year was analyzed to evaluate the effect of summer planting, whereas eighth-year survival was analyzed to focused on the effects of silvicultural practices. Explanatory variables in the survival models included height and H:D ratio at planting, seedling type, inside or outside the forwarder trail and plot.

For height and RCD eight years post-planting, LMMs were implemented using the *lmer* function from the "lmerTest" package [50]. The growth model included plot as a random factor, with the remaining variables of survival models acting as explanatory variables. These LMM analyses provide an alternative approach to the 8-year RGR_H and RGR_D analyses, offering deeper insights into the complex effects of the investigated factors.

Explanatory variable multicollinearity was confirmed using adjusted generalized standard error inflation factors (values < 3) through the "car" package's *vif* function [51]. H:D ratio was chosen over RCD as the initial seedling shape value owing to limited RCD overlap between bareroot and container seedlings.

For GLMs and LMMs, Akaike's information criterion (AIC)-based model selection was performed using the "MuMIn" package's *dredge* function [52]. No significant difference emerged between JFA150 and JFA300 container seedlings in preliminary analyses (JFA150 and JFA300 values, respectively, with *p*-values for type II analysis of deviance. Survival rates in the second year were as follows: 96% and 99%, *p* = 1.00. Survival in the eighth year was as follows: 79% and 74%, *p* = 0.61; height after eight years was 206 cm and 216 cm, *p* = 0.16; and RCD after eight years was 43.8 mm and 46.4 mm, *p* = 0.20). Consequently, JFA150 and JFA300 were treated as undifferentiated container seedlings.

2.3.4. Analyses of Survival Decline in the Sixth Year in the Forwarder Trail and Height Growth and Competition in the Fifth Year

To analyze the relationship of the sixth-year survival decline in the forwarder trail with seedling size, LMMs were applied to container seedlings surviving in the forwarder trail until the fifth year. Height and RCD differences were assessed between these surviving seedlings and those that died in the sixth year. In addition, LMMs were used to investigate RGR_H and RGR_D differences in the fifth year between seedlings competing with dwarf bamboo and those with deciduous vegetation. This analysis included random effects of plot and stock type. Three seedlings in competition with deciduous herbs, *Carex* sp., were excluded from the analysis data due to substantial soil moisture and thus small seedling size. All LMMs were analyzed using the *lmer* function. Notably, although weeding was performed in the summer of the fifth year, the height growth of Sakhalin fir seedlings in that year should have been completed prior to weeding and thus not affected by vegetation release, as the height growth of Sakhalin fir seedling typically reaches a plateau by late June [53].

3. Results

3.1. Competing Vegetation

In 2018, three years post-MSP, the competing vegetation that covered each study seedling the most was, in order of frequency of occurrence, the deciduous tree *Betula platyphylla* Sukaczew, the deciduous shrub *Rubus idaeus* L. subsp. *melanolasius* Focke and *Aralia elata* (Miq.) Seem, followed by the evergreen dwarf bamboo *S. senanensis*. Deciduous shrubs and trees represented 43% and 30% of the total frequency, respectively, with dwarf bamboo accounting for only 17% (Figure 2a). Vegetation height was ~80–150 cm for trees, shrubs, and dwarf bamboo, comparable to Sakhalin fir seedling height. In contrast, herb height was ~30–80 cm (Figure 2b). Planted Sakhalin fir seedlings maintained a marked height advantage over dwarf bamboo after six years (Figure S5), and this trend persisted at the end of the study period, eight years after planting.

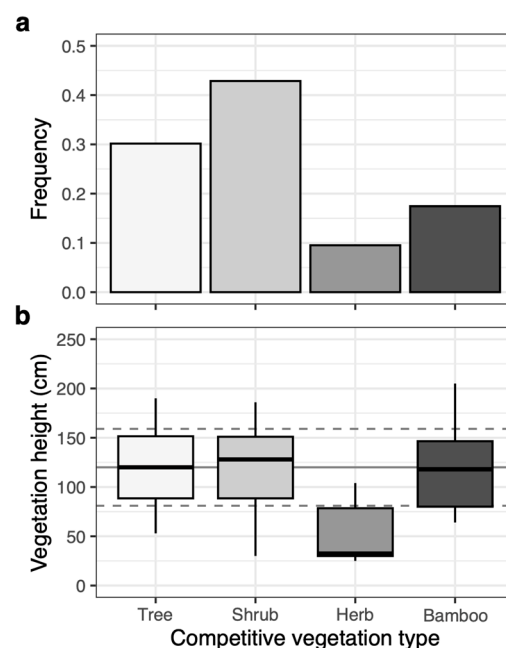


Figure 2. (a) Frequency of occurrence and (b) height of competing vegetation classified by life form in June 2018, three years after mechanical site preparation and planting. Solid and dashed gray lines in panel (b) represent the mean and standard deviation of the height of Sakhalin fir seedlings in late fall 2018.

3.2. Survival Rate

Sakhalin fir seedlings planted in July outside the forwarder trail in standard reforestation soil exhibited >10% reduced survival in the first year for bareroot seedlings, whereas both container seedling types exhibited high survival rates (Figure 3a). From the second to eighth year of planting, all stock types consistently achieved survival rates $\geq 95\%$ (Figure 3a), leading to >75% survival at the study's end (Figure 3b). Comparing container seedling survival inside and outside the forwarder trail, annual survival rates tended to be lower within the trail in the sixth and seventh years (Figure 3c), resulting in a cumulative survival rate of 65% inside the trail, contrasting with 82% outside the trail after eight years (Figure 3d). Regarding container seedlings inside the forwarder trail, analysis of surviving and dead seedlings in the sixth year showed that surviving seedlings had significantly greater height and RCD than their deceased counterparts (height: $p = 0.0016$; RCD: $p = 0.0016$; Table 2).

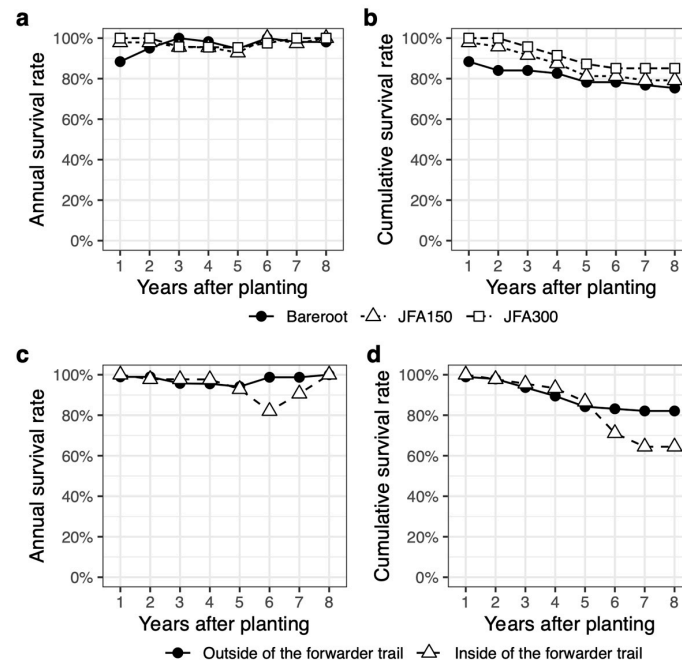


Figure 3. Eight-year variation in the survival rate of summer-planted Sakhalin fir seedlings. (a,c): Annual survival rate; (b,d): cumulative survival rate. Comparisons among (a,b) stock types and (c,d) comparison between outside and inside the forwarder trail for container seedlings.

Table 2. Comparison of height and root collar diameter (RCD) five years after planting between surviving and dead container seedlings on the forwarder trail in the sixth year. Mean $\pm$ standard error with corresponding p -values from the linear mixed model. **: $p < 0.01$.

	Height (cm)	RCD (mm)	<i>n</i>
Surviving	87 $\pm$ 6	22.1 $\pm$ 1.4	32
Dead	39 $\pm$ 9	11.7 $\pm$ 1.5	7
<i>p</i> -value	0.0016 **	0.0016 **	

The GLM for two-year survival with the lowest AIC included stock type and plot effects as explanatory variables (Table 3). Container seedlings showed a significant positive effect on two-year survival compared with bareroot seedlings ($p < 0.001$; Table 3). The upper-mulcher + rake plot exhibited a nonsignificant negative effect compared with the lower-bucket plot. For eight-year survival, GLM with the lowest AIC included stock type and forwarder trail effects as explanatory variables. Inside the forwarder trail exhibited a significantly negative impact on eight-year survival compared with outside ($p = 0.006$)), whereas container seedlings showed a positive nonsignificant effect on eight-year survival.

Table 3. Explanatory variable results in the best general linear models for two-year and eight-year survival, selected based on Akaike's information criterion. Significant effects are indicated in bold.

Fixed Effects	Category	Two-Year Survival				Eight-Year Survival			
		Estimate	SE	<i>z</i> -Value	<i>p</i> -Value	Estimate	SE	<i>z</i> -Value	<i>p</i> -Value
Intercept		1.61	0.53	3.00	0.002	−0.05	0.47	−0.12	0.908
Stock type (vs. bareroot)	Container	2.07	0.56	3.69	<0.001	0.54	0.37	1.45	0.143
Forwarder trail (vs. outside trail)	Inside trail			Not selected		−1.08	0.39	2.74	0.006
Initial height				Not selected				Not selected	
Initial H:D ratio				Not selected				Not selected	
Plot	Middle-mulcher	0.25	0.71	0.35	0.728			Not selected	
(vs. lower-bucket)	Upper-mulcher + rake	−0.87	0.62	−1.40	0.163			Not selected	

3.3. Seedling Growth

For seedlings planted in standard soil outside the forwarder trail, bareroot seedlings exhibited significantly higher height and RCD at planting compared with container seedlings. This disparity persisted for eight years post-planting, although no significant difference compared with JFA300 seedlings was noted in the sixth and eighth years (Figure 4a,b). Although JFA150 seedlings were significantly taller than JFA300 seedlings at planting, the difference became insignificant after one year. The H:D ratio was significantly higher in container seedlings relative to bareroot seedlings at planting, subsequently declining in container seedlings by the second year, and maintaining minimal differences among seedlings or years after the third year (Figure 4c).

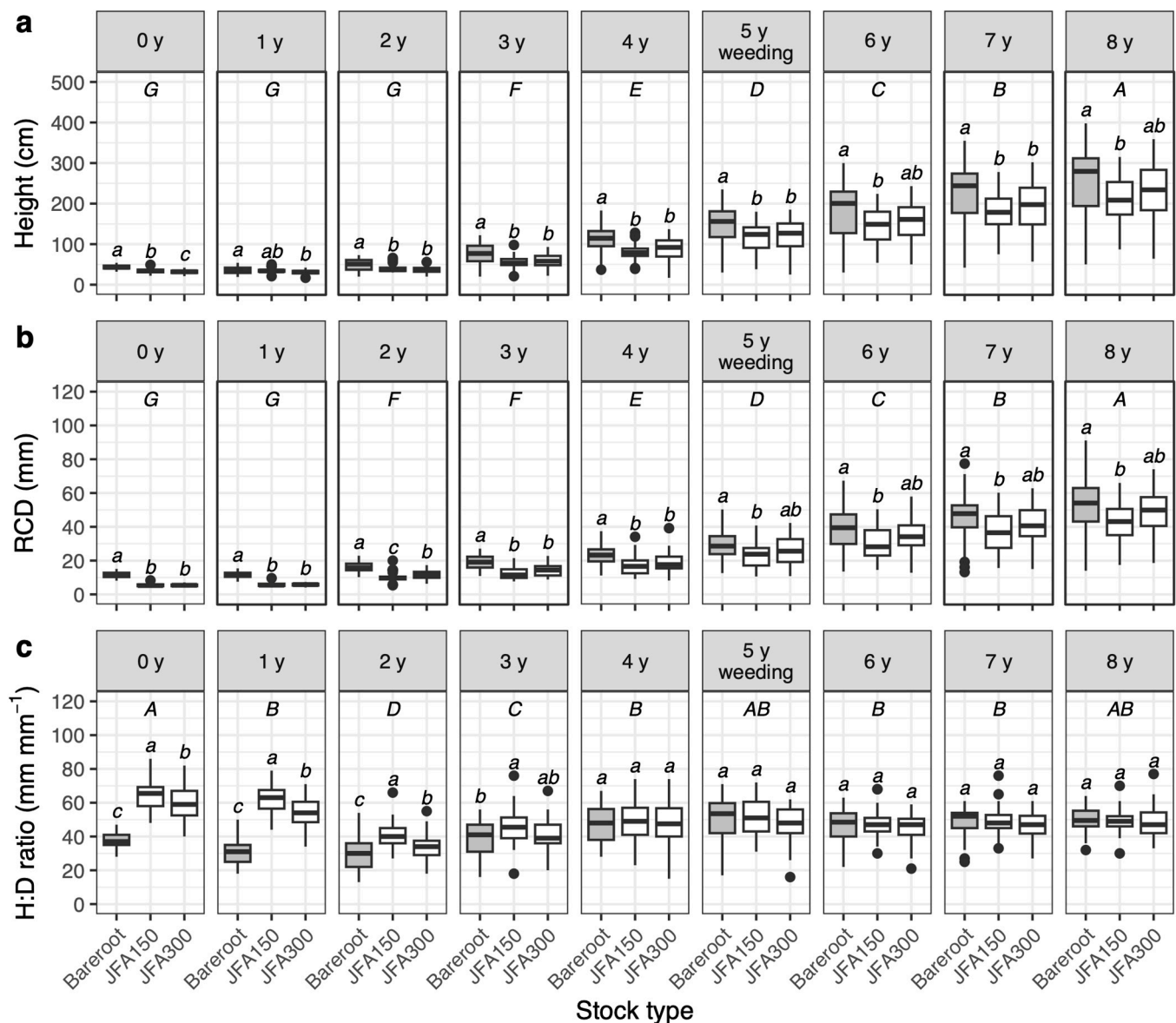


Figure 4. Comparisons among stock types for eight-year variation in (a) height, (b) root collar diameter (RCD), and (c) height/RCD (H:D) ratio of Sakhalin fir seedlings planted outside the forwarder trail in summer 2015. Weeding was performed only in the fifth year of the eight-year period. The term “0 year” represents the period immediately after planting. Different lowercase letters indicate significant differences between stock types in each year, whereas different uppercase letters indicate significant differences among years ($p < 0.05$).

Owing to apical shoot death induced by summer planting, bareroot seedlings demonstrated a remarkably negative RGR_H in the first year, significantly lower than container seedlings (Figure 5a). From the second year onward, all stock types displayed predominantly positive RGR_H until the eighth year, with negligible differences among them after the third year. RGR_D was significantly lower in bareroot seedlings compared with the two types of container seedlings in the first and second years, maintaining relatively consistent values among stock types after the third year (Figure 5b). In terms of year-wise differences, RGR_H reached its lowest and highest levels in the first and third year, respectively (Figure 5a), whereas RGR_D was lowest and highest in the first and second year, respectively (Figure 5b). There was no discernable trend for higher RGR_H and RGR_D in the fifth year with weeding or the subsequent year compared to the preceding year.

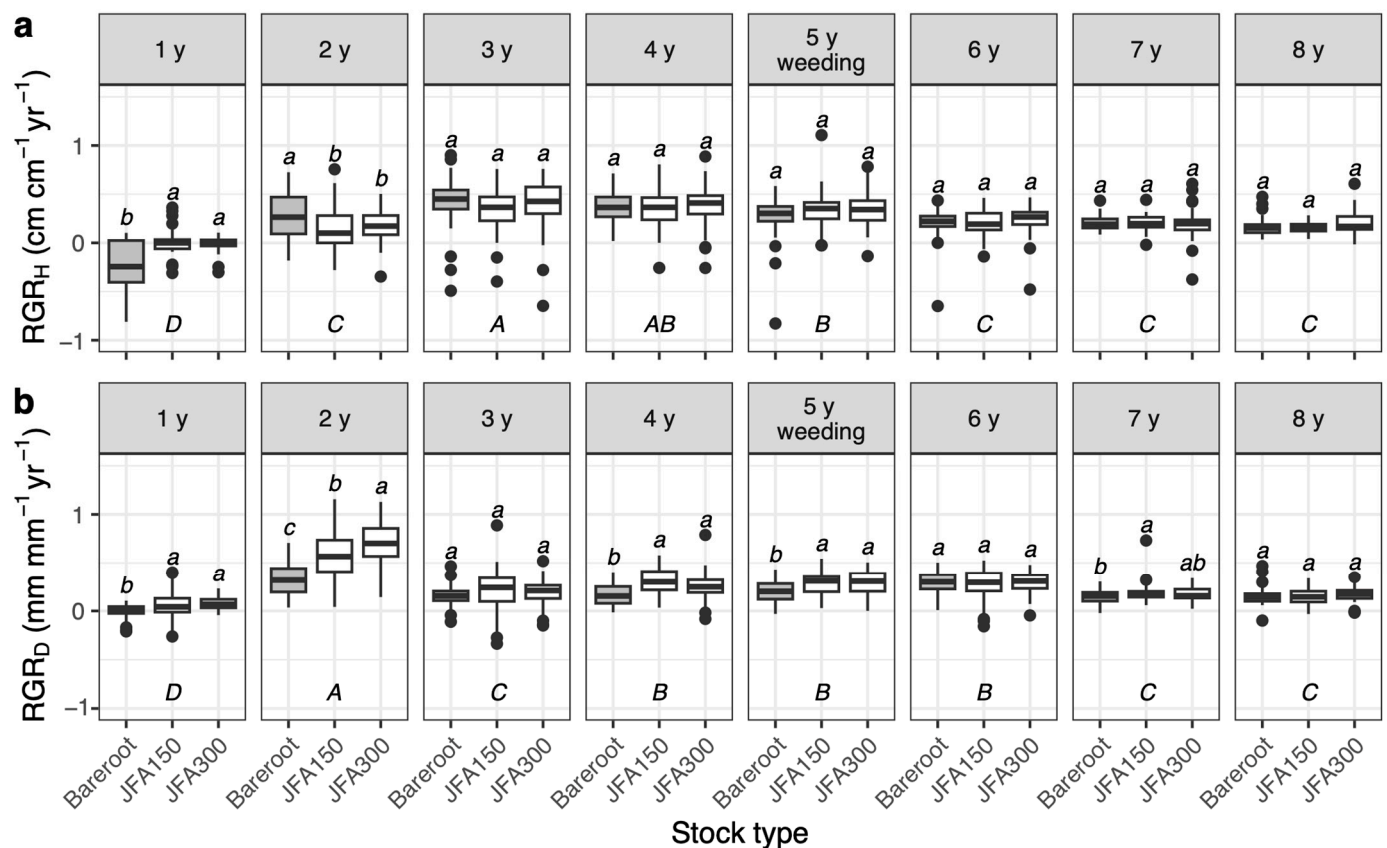


Figure 5. Comparisons among stock types for eight-year variation in (a) relative growth rate of height (RGR_H) and (b) relative growth rate of root collar diameter (RGR_D) of Sakhalin fir seedlings planted outside the forwarder trail in summer 2015. Weeding was performed only in the fifth year of the eight-year period. Different lowercase letters indicate significant differences between stock types in each year, whereas different uppercase letters indicate significant differences among years ($p < 0.05$).

Comparing container seedlings positioned inside and outside the forwarder trail, seedling height was significantly greater outside the trail from the second- to the eighth-year post-planting (Figure 6a). RCD was significantly higher outside the trail from the second- to the fifth-year post-planting, with no significant difference observed from the sixth to the eighth year (Figure 6b). H:D ratio also showed significance, with values outside the trail being higher from the fourth to eighth year (Figure 6c). Although RGR_H was significantly higher outside the trail from the second- to fourth-year post-planting, no consistent trend emerged after the fifth year (Figure 7a). RGR_D was significantly higher outside the trail in the second year after planting, with no significant differences observed in other years, except for the fifth year (Figure 7b).

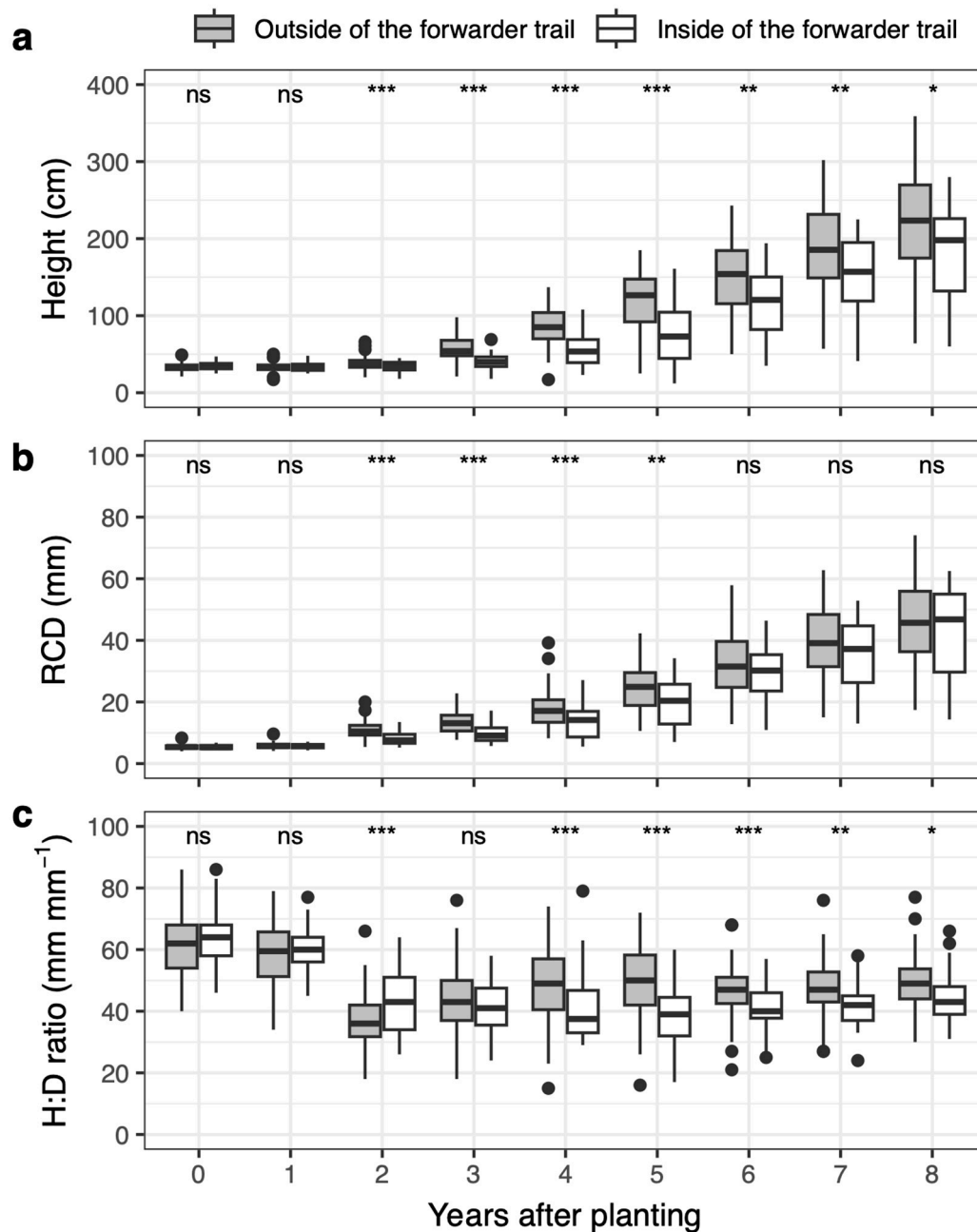


Figure 6. Comparisons between outside and inside the forwarder trail for eight-year variation in (a) height, (b) root collar diameter (RCD), and (c) height/RCD (H:D) ratio of container Sakhalin fir seedlings planted in summer 2015. Weeding was performed only in the fifth year of the eight-year period. “0 years” represents immediately after planting. Asterisks indicate significant differences inside and outside the forwarder trail: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns $p \geq 0.05$.

For seedling height eight years post-planting, the best LMM included significant initial height and forwarder trail effects, indicating positive and negative effects from initial height and planting inside the forwarder trail, respectively (Table 4). The best LMM for RCD eight years post-planting had no significant effects.

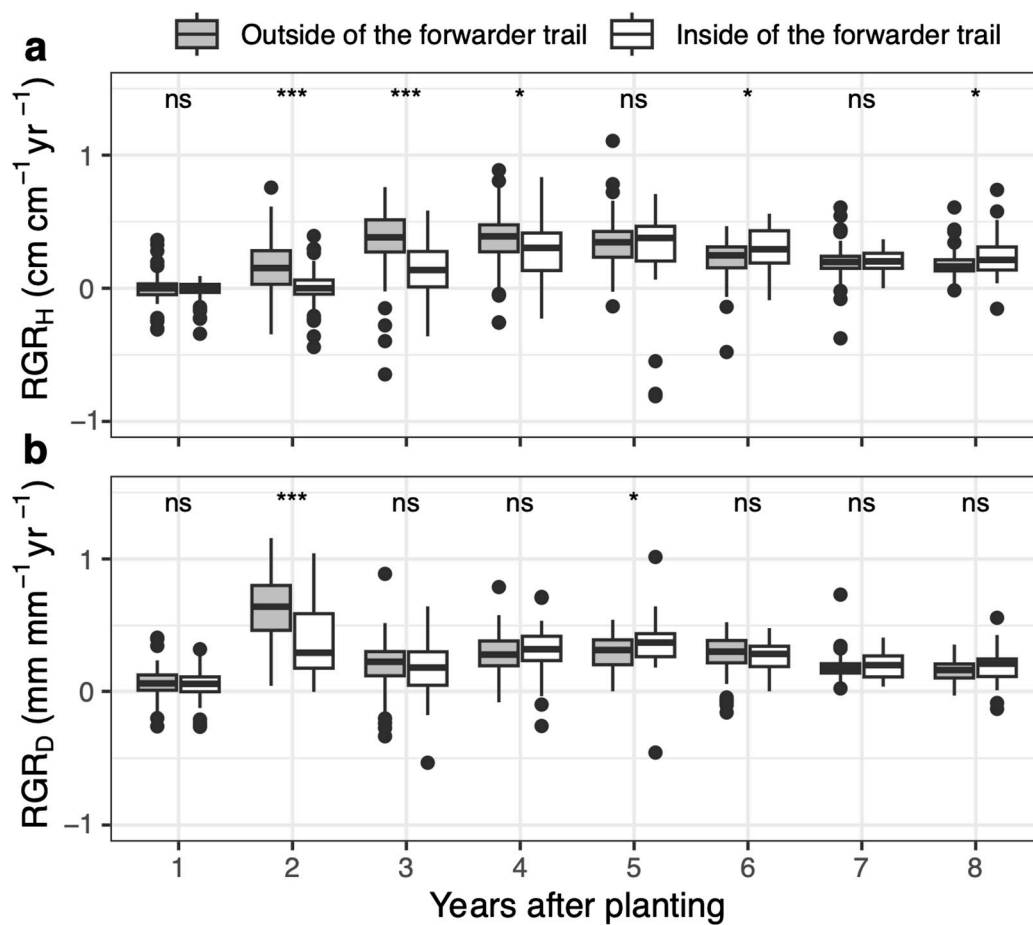


Figure 7. Comparisons between outside and inside the forwarder trail for eight-year variation in (a) relative growth rate of height (RGR_H) and (b) root collar diameter (RGR_D) of container Sakhalin fir seedlings planted in summer 2015. Asterisks indicate significant differences inside and outside the forwarder trail: *** $p < 0.001$; * $p < 0.05$; ns $p \geq 0.05$.

Table 4. Explanatory variable results in the best linear mixed models for seedling height and root collar diameter (RCD) eight years post-planting, selected based on Akaike's information criterion. Significant effects are shown in bold.

Fixed Effects	Category	Height after Eight Years				RCD after Eight Years			
		Estimate	SE	<i>t</i> -Value	<i>p</i> -Value	Estimate	SE	<i>t</i> -Value	<i>p</i> -Value
Intercept		131.9	49.3	2.68	0.008	37.5	10.36	25.76	<0.001
Initial height		2.9	1.1	2.63	0.009	0.34	0.23	1.47	0.145
Initial H:D ratio		Not selected				Not selected			
Stock type (vs. bareroot)	Container	−8.7	16.8	−0.52	0.605	−3.03	3.52	−0.86	0.392
Forwarder trail (vs. outside trail)	Inside	−40.1	15.2	−2.64	0.009	−3.33	3.19	−1.05	0.298

In a comparison of growth in the fifth year between seedlings competing with deciduous woody and herbaceous vegetation versus evergreen dwarf bamboo, RGR_H was significantly lower with evergreen dwarf bamboo compared to deciduous vegetation (Figure 8a). However, RGR_D exhibited no significant differences between the two vegetation types (Figure 8b).

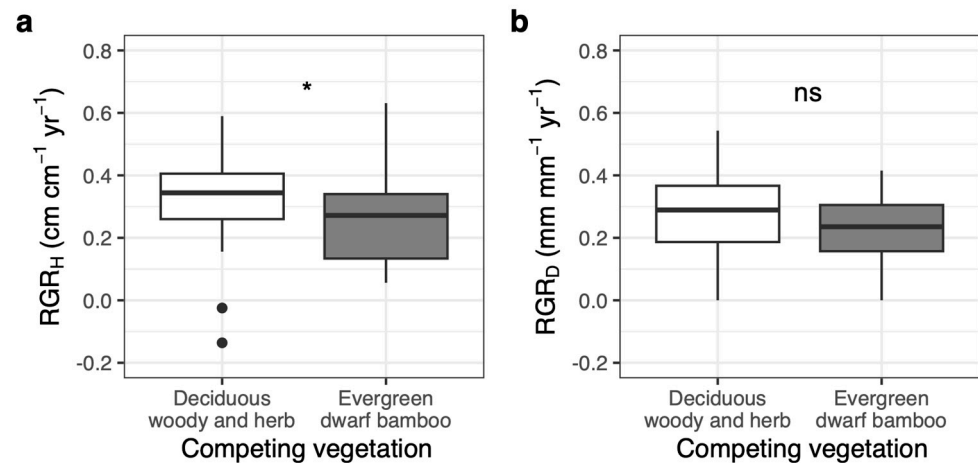


Figure 8. Comparisons between Sakhalin fir seedlings competing with deciduous vegetation and those competing with evergreen dwarf bamboo in terms of (a) relative growth rate of height (RGR_H) and (b) root collar diameter (RGR_D) in the fifth year. Asterisks indicate significant differences based on linear mixed models: * $p < 0.05$; ns $p \geq 0.05$.

4. Discussion

4.1. Success in Sakhalin Fir Reforestation with One Weeding Operation in Eight Years

In this comprehensive study, where the entire reforested area was subjected to MSP, the planted Sakhalin fir seedlings exhibited no significant decline in survival or growth rate over an eight-year period (Figures 3–5) despite facing competitive vegetation with a single weeding operation in the fifth year. The successful reforestation, without conventional weeding sustained for seven consecutive years [10], can be attributed to the extensive implementation of MSP, which effectively eradicated the potentially robust competitor, evergreen dwarf bamboo (*S. senanensis*). This intervention involved bucket scarification and mulching via a forestry mulcher across the site, leading to the replacement of dwarf bamboo with deciduous woody and herbaceous plant growth post-MSP (Figure 2). Previous studies also highlighted the efficacy of intense scarification treatments in curbing *S. senanensis* resurgence, thereby enhancing Sakhalin fir regeneration and survival in a mixed boreal temperate forest under selective logging [54–56].

Although this study included a less dense proliferation of dwarf bamboo (Figure 2) compared with typical growth patterns (Figure S1), the competitive influence of dwarf bamboo still resulted in reduced height growth of Sakhalin fir seedlings, especially in comparison to competing with deciduous vegetation (Figure 8a). Had whole-site MSP not been implemented and weeding executed only once over the eight-year planting period, a denser dwarf bamboo cover would have likely ensued, intensifying the coverage of planted seedlings and markedly hampering their growth and survival.

Conversely, the post-MSP regeneration of deciduous trees, shrubs, and herbs throughout the reforested area showed diminished competitiveness with the established Sakhalin fir seedlings (Figure 8a). Evidently, RGR_H and RGR_D displayed no consistent increase following vegetation release after fifth-year weeding (Figure 5). Sakhalin fir is renowned for being highly shade-tolerant [33,34,57], this trend is consistent with findings suggesting that shade-tolerant tree species experience minimal growth variation before and after vegetation release [58]. Notably, the competing vegetation in this site, largely composed of deciduous trees and herbs (76%; Figure 2a), achieved a height similar to that of Sakhalin fir seedlings (Figure 2b) during this period. The evergreen nature of Sakhalin fir seedlings enables them to use bright light for photosynthesis before leaf expansion in early spring and after leaf shedding in late autumn when the deciduous vegetation canopy remains underdeveloped. This feature is particularly advantageous as the growth of the current-year shoots in evergreen conifers depends on photosynthates assimilated by preexisting shoots during spring to early summer [59–61]. The abundant light availability during spring, when deciduous

species pose as competitors, augments Sakhalin fir seedling growth. These combined factors contribute to the success of Sakhalin fir reforestation, with minimal weeding performed over eight years, ensuring little impact on their survival and growth.

While our study focuses on the specific case of Sakhalin fir and dwarf bamboo in Hokkaido, Japan, the approach of using MSP to reduce competitive vegetation pressure by suppressing highly competitive vegetation and changing the composition of competing vegetation species could potentially be adapted to other regions. Our results suggest that the effectiveness of MSP may vary depending on the shade tolerance of the target tree seedlings and the leaf habit (evergreen or deciduous) of both the target seedlings and the competing vegetation. Future studies should investigate the effects of varying weeding timings on Sakhalin fir growth and competitive vegetation recovery. This will provide valuable insights into optimizing weeding practices for enhancing Sakhalin fir growth.

4.2. Negative Effects of Forwarder Trail

The forwarder trail yielded significant negative effects on the survival and growth of implanted Sakhalin fir seedlings, with timing variations noted for survival, RGR_H , and RGR_D (Figure 3c,d and Figure 6a,b; Tables 3 and 4). Although heavy machinery typically exerts its most pronounced influence immediately after operation, without a cumulative increase over time [39,62,63], a noteworthy finding was the significant negative survival effect appearing in the sixth year following the operation (Figure 3c), rather than promptly postoperation. The sixth-year survival downturn on the forwarder trail may be attributed to soil desiccation due to low July precipitation in that year (2020), totaling a mere 44 mm, approximately one-third of the normal level (Figure S6b), accompanied by only four days of rainfall in July (Figure S6c). The repeated passage of heavy machinery can induce soil compaction, diminishing water permeability, hydraulic conductivity, soil macropore space, and root expansion and elongation, and ultimately reducing plant water availability [40,64–66]. In the present study, the forwarder traversed wet soils during light rain or immediately after rainfall on a relatively steep slope of approximately 20°, implying severe soil compaction [39,67]. The recovery of severe soil compaction generally takes more than a decade and may not reach full recovery [39,62,63,68], whereas mild compaction can be fully restored [69,70]. Moreover, the adverse effects of compaction on tree seedlings in brown forest soil, as in the current study, are documented elsewhere [44,63,71], although the impact of soil compaction on tree seedlings varies by soil type [45].

Significantly smaller individuals died on the forwarder trails in the sixth year (Table 2), implying that compacted soil inhibited both root elongation and height growth [72], thereby impeding water absorption during the drought in that summer and causing desiccation-induced death [67]. Individuals of smaller size are generally more likely to be covered by other vegetation. However, the limited vegetation growth on the forwarder trails meant that cover should not be a mortality factor (Figure 1c). Despite similarly low July precipitation levels in the seventh and eighth years (2021 and 2022, respectively; Figure S6), survival rates were not significantly reduced in these years (Figure 3c). This result may be attributed to robust survivors of the sixth year of summer drought possessing deep roots in the moist soil, enabling water absorption during subsequent droughts, and safeguarding against mortality in the sixth to eighth years, which were marked by summer drought.

Regarding growth dynamics, the forwarder trail negatively affected RGR_H up to the fourth-year post-planting (Figure 7a), whereas RGR_D was negatively affected only in the second year (Figure 7b). This dissimilarity in duration can be attributable to two factors. The first is that the forwarder trails are susceptible to soil drying due to soil compaction, as described above, resulting in significantly reduced height growth, which is generally more sensitive to drought stress than RCD growth [73,74], as seen with bareroot seedlings after summer planting in this study (Figure 5a). The second is that forwarder trails are less prone to competitive vegetation growth, and tree seedlings are more likely to favor height growth over diameter expansion under competitive conditions [4,75,76]. Although soil compaction can directly impede tree seedling growth [39,45,64], it can indirectly promote

growth by inhibiting the growth of competitive vegetation (Figure 1c) [77]. Consequently, growth reduction due to soil compaction was absent outside the forwarder trail, whereas negative effects from competing vegetation were more pronounced for RCD than for height growth. Contrastingly, within the forwarder trail, discernible growth reduction owing to soil compaction was prominent in competing vegetation. Thus, RCD growth within the forwarder trail possibly reached levels akin to those outside the trail earlier than height growth. The relatively limited influence of soil compaction on diameter growth compared with height growth in meta-analyses examining soil compaction effects [43,45] may be due in part to the suppression of competing vegetation overgrowth by soil compaction, as shown in the present study, as well as to the inhibition of height growth due to soil drying. As global warming is predicted to increase the frequency of extreme weather events, the adverse effects of heavy equipment travel routes, such as forwarder trails, may become a more significant issue in reforestation in the future.

4.3. Effects of Stock Type and Summer Planting

The influence of summer planting on the growth and survival of Sakhalin fir seedlings exhibited stock type divergence, with container seedlings showing greater resilience to negative effects compared with bareroot seedlings (Figures 3 and 4). This aligns with the general tendency for container seedlings to endure transplant shock and challenging site conditions more effectively [38]. A study summarizing Sakhalin fir container seedling planting trials in Hokkaido also revealed robust survival rates exceeding 90% in 13 out of 16 cases for June–September planting, a period deemed unsuitable for planting bareroot seedlings [78]. These findings support the feasibility of summer planting for Sakhalin fir container seedlings.

Despite July being considered unfavorable for bareroot seedling planting, a notably high cumulative survival rate exceeding 80% was evident in the second planting year (Figure 3b). This outcome can be attributed to significantly higher than average pre-planting and post-planting rainfall in this study (Figure S2), with July precipitation in the planting year double the historical average for that month (Figure S6). This increased soil moisture effectively mitigated planting shock, explaining the observed high survival rate in bareroot seedlings. Nonetheless, a noticeable reduction in height due to apical shoot dieback was observed exclusively in bareroot seedlings (Figure 5a), suggesting that, under typical rainfall conditions, bareroot seedling survival would likely be even lower than in this study.

After eight years of summer planting, seedling height and RCD tended to be greater for bareroot seedlings than for container seedlings (Figure 4a,b). However, growth rates exhibited minimal divergence between stock types beyond the third year (Figure 5a,b). LMM analyses revealed that the observed height advantage of bareroot seedlings after eight years was primarily attributed to their larger initial height, rather than a simple stock-type effect (Table 4). These findings are consistent with the general trend that once acclimatized in the field, both bareroot and container seedlings show comparable growth rates, with larger seedlings at planting yielding better growth [38]. In the present study, the influence of initial seedling height on height and RCD after eight years may have been diminished compared with conventional site preparation methods, given that MSP shifted competitive vegetation from the highly competitive dwarf bamboo to less competitive deciduous vegetation (Figure 2). In other words, the typical advantage of taller seedlings outgrowing competing vegetation [79–81] may have been diluted in the presence of less competitive vegetation due to the strong shade tolerance of Sakhalin fir.

Planting bareroot seedlings during the optimal spring or fall seasons would likely lead to a more pronounced height difference between bareroot and container seedlings after eight years, because there will be no top-shoot withering due to summer planting. While container seedlings are often smaller than bareroot seedlings globally as demonstrated in this study (Figure 4a,b), advancements of seedling production programs could yield larger container seedlings [38]. Equivalently sized container seedlings can perform equally

well [80] or even outperform bareroot seedlings [82]. The smaller container seedlings with a higher H:D ratio at planting tend to prioritize diameter growth over height until reaching a more balanced ratio [30,83]. In this study, container seedlings with higher H:D ratio (Figure 4c) exhibited high RGR_D and low RGR_H in the second year (Figure 5a,b), suggesting potential for improved growth with optimized production practices leading to larger and more suitable H:D ratios in Sakhalin fir container seedlings.

5. Conclusions

MSP can alter vegetation from highly competitive dwarf bamboo to less competitive deciduous trees and herbs. Consequently, even when the weeding frequency is reduced from the conventional once a year for seven consecutive years to once in the fifth year, the survival and growth of shade-tolerant Sakhalin fir seedlings can be maintained, significantly reducing the weeding costs. Additionally, planting within compacted soil forwarder trails negatively impacts seedling survival and growth, with reduced survival due to low summer rainfall, even six years post-planting. Furthermore, summer planting of container Sakhalin fir seedlings minimally affects survival and growth, and taller container seedlings with the appropriate H:D ratio exhibit improved post-planting growth.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/f15061012/s1>, Figure S1: Photographs of typical evergreen dwarf bamboo dominating the understory in Hokkaido, northern Japan; Figure S2: Meteorological data around the time of harvest obtained using a cut-to-length (CTL) system, followed by mechanical site preparation (MSP) and planting in 2015; Figure S3: Comparisons among plots with different mechanical site preparation (MSP) and slope position for eight-year variation in (a) height, (b) root collar diameter (RCD), and (c) height:RCD (H:D) ratio of Sakhalin fir seedlings planted outside the forwarder trail in summer 2015; Figure S4: Comparisons among plots with different mechanical site preparation (MSP) and slope position for eight-year variation in (a) relative growth rate of height (RGR_H) and (b) relative growth rate of root collar diameter (RGR_D) of Sakhalin fir seedlings planted outside the forwarder trail in summer 2015; Figure S5: Photos of evergreen dwarf bamboo regeneration at the study site in 11 May 2021 (six years after mechanical site preparation); Figure S6: Meteorological data from the growing seasons (May–October) during the study period.

Author Contributions: Conceptualization: H.H. and H.U.; Methodology: H.H.; Formal analysis and investigation: H.H., I.T., T.Y., M.K., N.F., K.Y., T.S., A.U., S.S. and H.U.; Writing—original draft preparation: H.H.; Writing—review and editing: H.H., I.T., T.Y., M.K., N.F., K.Y., T.S., S.S. and H.U.; Funding acquisition: H.H., S.S. and H.U. All authors contributed to the article and approved the submitted version. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the Ministry of Agriculture, Forestry, and Fisheries of Japan (25093C, 18064868) and the Forestry Insurance Center (“Advanced evaluation of meteorological damage risk based on the elucidation of the damage process”).

Data Availability Statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Acknowledgments: We would like to thank Tomohiro Saitou of the Shimokawa Town Government for providing and managing the study site, and Mitsutoshi Umemura, Qingmin Han, Takami Saito, Tatsuya Sasaki, Daisuke Kabeya, Toshimitsu Nagasawa, and Haruka Yamamoto of the Forestry and Forest Products Research Institute for helping with field investigations and data entry.

Conflicts of Interest: The authors declare no conflicts of interest.

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